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Marine propulsion load emulation

Johnson, Philip N.

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NAVAL POSTGRADUATE SCHOOL
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THESIS

MARINE PROPULSION LOAD EMULATION

by

Philip N. Johnson

June 1985

Thesis Advisor: David Smith

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Marine Propulsion Load Emulation

by

Philip N. Johnson
Lieutenant Commander, United States Navy
B.S.M.E. Maine Maritine Academy, 1977

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1985

ABSTRACT

Improved propulsion plant control schemes for gas turbine ships can provide both economic and tactical benefits to the fleet. One way to develope improved propulsion controllers is to use a marine propulsion emulator as an implementation test bed for proposed engine control logic.

This paper describes the development and implementation of a load control system for a marine propulsion emulator which uses a water filled dynamometer and a 160 horsepower gas turbine. Steady state and transient data were collected and analyzed and a dynamic dynamometer model was developed using the Continuous System Modelling Program CSMP III. A proportional plus derivative control system was designed using the nonlinear CSMP model with a cut-and-try design approach. Hardware control elements including valve positioners and microprocessor interfaces were designed and fabricated. The microprocessor-based controller was programed with the dynamometer control algorithm and the system was tested to verify the emulator design.

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SYMBOLS AND ABREVIATIONS

ADC	Analog to digital converter
CSMP	Continious System Modelling Program
DAC	Digital to analog converter
DGAIN	Derivative gain
Dl	Digital load signal
Du	Digital unload signal
DYNO	Dynamometer
err	error signal
Id	Dynamometer inertia (ft-lbf-sec^2)
IGAIN	Integral gain
Ipt	Power turbine and reduction gear inertia (ft-lbf-sec^2)
It	Total drivetrain inertia (ft-lbf-sec^2)
Mag	Gas generator air mass flow rate (lbm/min)
Mwl	Dynamometer load water flow rate (lbm/min)
Mwu	Dynamometer unload water flow rate (lbm/min)
Nd	Dynamometer speed (rpm)
Ngg	Gas generator speed (rpm)
Npt	Power turbine speed (rpm)
Pe	Enviromental pressure (in. hg.)
Pd	Dynamometer shell pressure (psi)
PD	Proportional derivative
PGAIN	Proportional gain
Pgg	Gas generator back pressure
PID	Proportional Integral Derivative
Ppt	Power turbine back pressure
rpm	revolutions per miniute
Td	Dynamometer torque (ft-lb)
Tpt	Power turbine torque (ft-lb)
Vl	Dynamometer load valve voltage
Vu	Dynamometer unload valve voltage
Ww	Dynamometer water weight (lbm)

%l	Dynamometer load valve percent open
%u	Dynamometer unload valve percent open

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I. INTRODUCTION

Improvement of marine propulsion control can provide increased ship performance. This performance may be measured in many different forms such as acceleration, fuel economy, and increased engine life.

Generally speaking, there is added complexity with better control systems and their development is often difficult, but several steps can be taken to reduce the risk involved in developing new propulsion systems. As a first step, computer based modelling and simulation have been relied upon heavily to design propulsion control schemes for the newer gas turbine propelled ships [Ref. 1]. These simulations have provided quick feedback at relatively low expense in the testing of control alternatives. This design work has been supplemented with shore-based test facilities to prove out control system implementations using actual equipment. In this way modifications can be more easily applied and tested before costly adaptation into the fleet. These installations can also be well instrumented to detect problems which may otherwise go unnoticed.

In the past few years the Naval Ship Engineering Center, Philadephia, has been performing dynamic testing of gas turbine control systems through the development of a marine propulsion emulator [Refs. 2,3]. Part of their work has centered around the developement of a dynamic control system which is capable of emulating a marine propulsion load. The work discussed in this thesis centers around the design of a similar dynamometer controller and data acquisition system which was developed on a smaller scale.

This thesis discusses all phases of the dynamometer control design cycle, from specifications through hardware selection and implementation.

II. DESIGN SPECIFICATIONS

A. CONTROL SPECIFICATIONS

The controller must provide the ability to control the dynamometer remotely, from outside the engine test cell. It must also provide easy interfacing between computer and operator. The controller must support two modes of control: first, independently selectable dynamometer speed for speeds from 500 to 3000 rpm; and second, marine propulsion emulation scheduled from selectable gas generator speed.

The controller should also allow for future expansion and provide easy modification of the control algorithm. The controller should provide safe and stable operation throughout the dynamometers operating range. The dynamometer controller must interface with an existing gas generator governor.

In order to perform marine propulsion emulation for gas generator transients, the dynamometer control system should be able to assume or shed 85 percent of it's full power dissipation capacity in 15 seconds. This will allow the dynamometer to maintain effective load emulation in the face of gas generator throttle changes. The controller should also have less than 5 percent overshoot to steady state conditions due to speed limitations on the power turbine. Anticipated follow-on work dictates the use of a maximum controller sampling and duty cycle of 100 milliseconds.

Total new equipment purchases must be limited to $1500 and all new equipment ordered must arrive within 90 days of project inception.

B. DATA COLLECTION AND DISPLAY SPECIFICATIONS

All data displayed under the old facility must be duplicated. The data acquisition system should record all variables normally taken by the students as well as perform an analysis of turbine and dynamometer efficiencies. Transient data should be displayed for a selected group of dynamic variables as shown in Table I.

The data acquisition system should be centered around the HP 85 desk top computer to be consistant with other department needs.

TABLE I

Data acquisition specifications

VARIABLE	UNITS	STEADY	TRANSIENT	COMPUTED
BAROMETERIC PRESSURE	IN.HG.	A		M
CELL PRESSURE FRONT	IN.H2O	A		
CELL PRESSURE REAR	IN.H2O	A		
CELL PRESSURE AVERAGE	IN.H2O	A		A
AIRFLOW BELL PRESSURE RIGHT	IN.H2O	A		
AIRFLOW BELL PRESSURE LEFT	IN.H2O	A		
AIRFLOW BELL PRESS AVERAGE	IN.H2O	A		A
COMPRESSOR DISCH PRESS RIGHT	IN.HG	A		
COMPRESSOR DISCH PRESS LEFT	IN.HG	A		
COMPRESSOR DISCH PRESS AVE.	IN.HG	A		A
NOZZLE BOX PRESSURE	IN.HG	A		
COMPRESSOR INLET TEMP. A	DEG. F	A		
COMPRESSOR INLET TEMP. B	DEG. F	A		
COMPRESSOR INLET TEMP. C	DEG. F	A		
COMPRESSOR INLET TEMP. D	DEG. F	A		
COMPRESSOR INLET TEMP. AVE	DEG. F	A		A
COMP. DISCH TEMP. RIGHT A	DEG. F	A		
COMP. DISCH TEMP. LEFT A	DEG. F	A		
COMP. DISCH TEMP. RIGHT B	DEG. F	A		
COMP. DISCH TEMP. LEFT B	DEG. F	A		
COMP. DISCH TEMP. AVERAGE	DEG. F	A		A
FUEL TEMP.	DEG. F	A		
TURBINE INLET TEMP. RIGHT A	DEG. F	A		
TURBINE INLET TEMP. LEFT A	DEG. F	A		
TURBINE INLET TEMP. RIGHT B	DEG. F	A		
TURBINE INLET TEMP. LEFT B	DEG. F	A		
TURBINE INLET TEMP. AVERAGE	DEG. F	A		A
EXHAUST TEMP. RIGHT A	DEG. F	A		
EXHAUST TEMP. LEFT A	DEG. F	A		
EXHAUST TEMP. RIGHT B	DEG. F	A		
EXHAUST TEMP. LEFT B	DEG. F	A		
EXHAUST TEMP. AVERAGE	DEG. F	A		
UPPER ROTOMETER	NONE	A		M
LOWER ROTOMETER	NONE	A		M
SPECIFIC GRAVITY	NONE	A		M

Table I
Data acquisition specifications (cont'd.)

VARIABLE	UNITS	STEADY	TRANSIENT	COMPUTED
TURBINE SPEED	RPM	A	A	
DYNAMOMETER SPEED	RPM	A	A	
DYNAMOMETER TORQUE	FT-LB	A	A	
FUEL FLOW SENSOR	NONE	A		
COMPRESSOR INLET TEMP.	DEG. R.	A		A
THETA	NONE	A		A
COMPRESSOR INLET PRESSURE	PSIA	A		A
DELTA	NONE	A		A
LOWER HEATING VALUE	BTU/LBM	A		A
CORRECTED TORQUE	FT-LB	A		A
CORRECTED COMPRESSOR SPEED	RPM	A		A
CORRECTED DYNAMOMETER SPEED	RPM	A		A
CORRECTED BRAKE HORSE POWER	HP	A		A
CORRECTED MASS FUEL FLOW	LBM/HR	A		A
BRAKE SPECIFIC FUEL CONSUMP.	LBM/HP-HR	A		A
BRAKE THERMAL EFF	PRECENT	A		A
CORRECTED MASS AIR FLOW	LBM/SEC	A		A
AIR FUEL RATIO	NONE	A		A
AVERAGE EXAUST TEMP.	DEG R.	A		A
COMPRESSOR PRESSURE RATIO	NONE	A		A
COMPRESSOR DISCHARGE TEMP.	DEG. R.	A		A
AVERAGE TURBINE INLET TEMP.	DEG. R.	A		A
IDEAL COMPRESSOR EFF.	PERCENT	A		A

M = Entered manually
A = Automatically provided

III. APPROACH

A. EVALUATION OF SYSTEM FUNCTION

The preexisting engine test system is shown in Fig 3.1. The system is composed of two components: one for power production, and one for power dissipation.

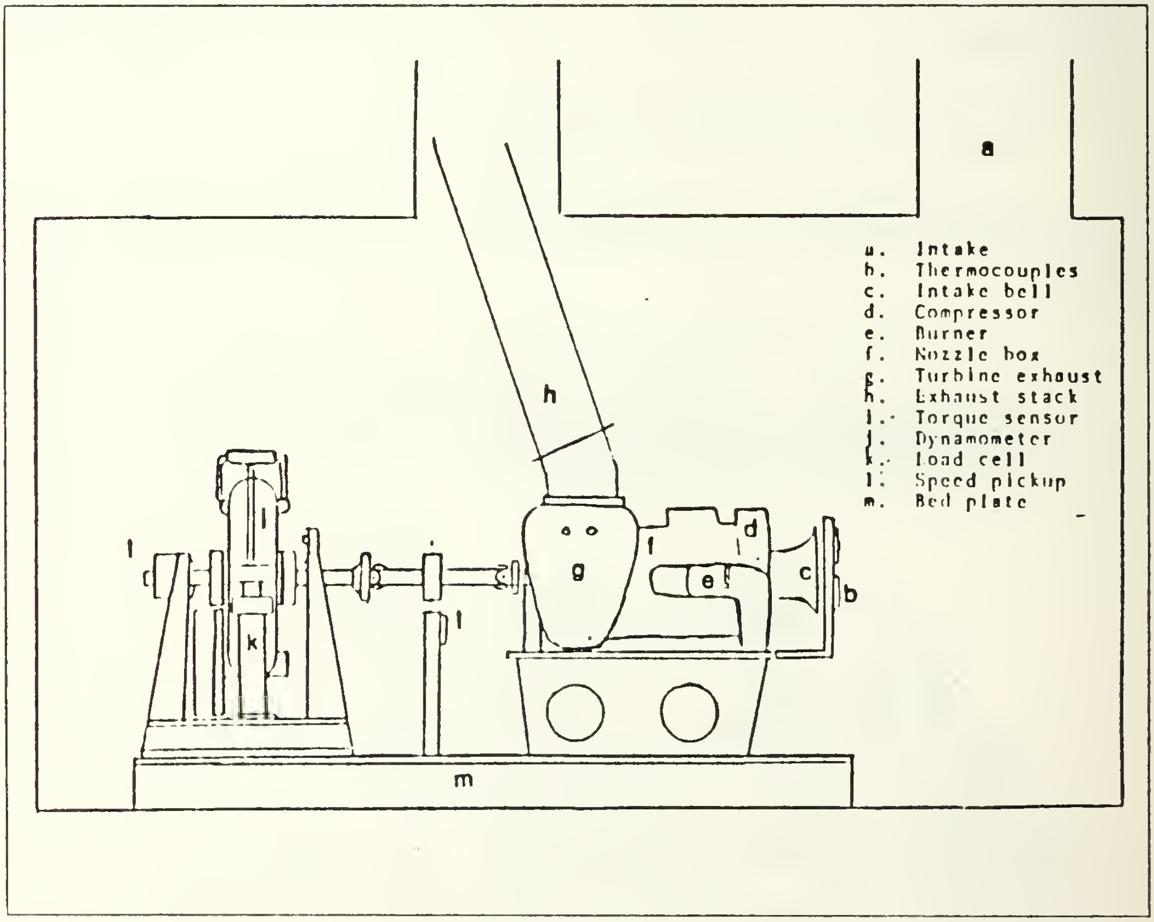

Figure 3.1 Test Cell Configuration.

The power production component consists of a Boeing model 502-2E gas turbine which has two major sections: a gas

generator, and a power output section. The gas generator contains a single-entry centrifugal compressor mechanically coupled to a single-stage axial-flow turbine, two cross-connected can type combustion chambers, and an accessory-drive section. The power output section incorporates a second axial-flow turbine, reduction gears and output shaft, and is driven by the gas generator by a flow of hot gas. The two turbines are not mechanically connected. This arrangement permits the gas generator speed to be controlled independently of the output shaft speed. The resulting engine has output shaft speed variable from 0 to 120 per cent of rated rpm (2900 rpm) for either full or part throttle operation.

The other major component in the test cell is the Claton 17-300 water dynamometer which absorbs the power output from the turbine. It consists of two sub-components: the power absorption unit and the heat exchanger. The power absorption unit may be thought of as a centrifugal water pump with rotor and stator vanes producing a shearing action on the contained water. The torque produced by this shearing action causes the power absorption unit to try to rotate axially on cradle bearings, thus exerting force on a restraining load cell. The quantity of water within the power absorption unit is relatively small, ranging from .5 to 48 lbs. To keep this water at safe operating temperatures the water is circulated by the pumping action of the rotor to the second sub-component, the heat exchanger. An automatic temperature control valve regulates the cooling water to provide near constant water operating temperature.

The unmodified system is dissected into it's major functional components in Fig 3.2. The results of a multiport analysis are shown in the Figure which shows how power is exchanged between the various components. Of special interest are those components which interface with the

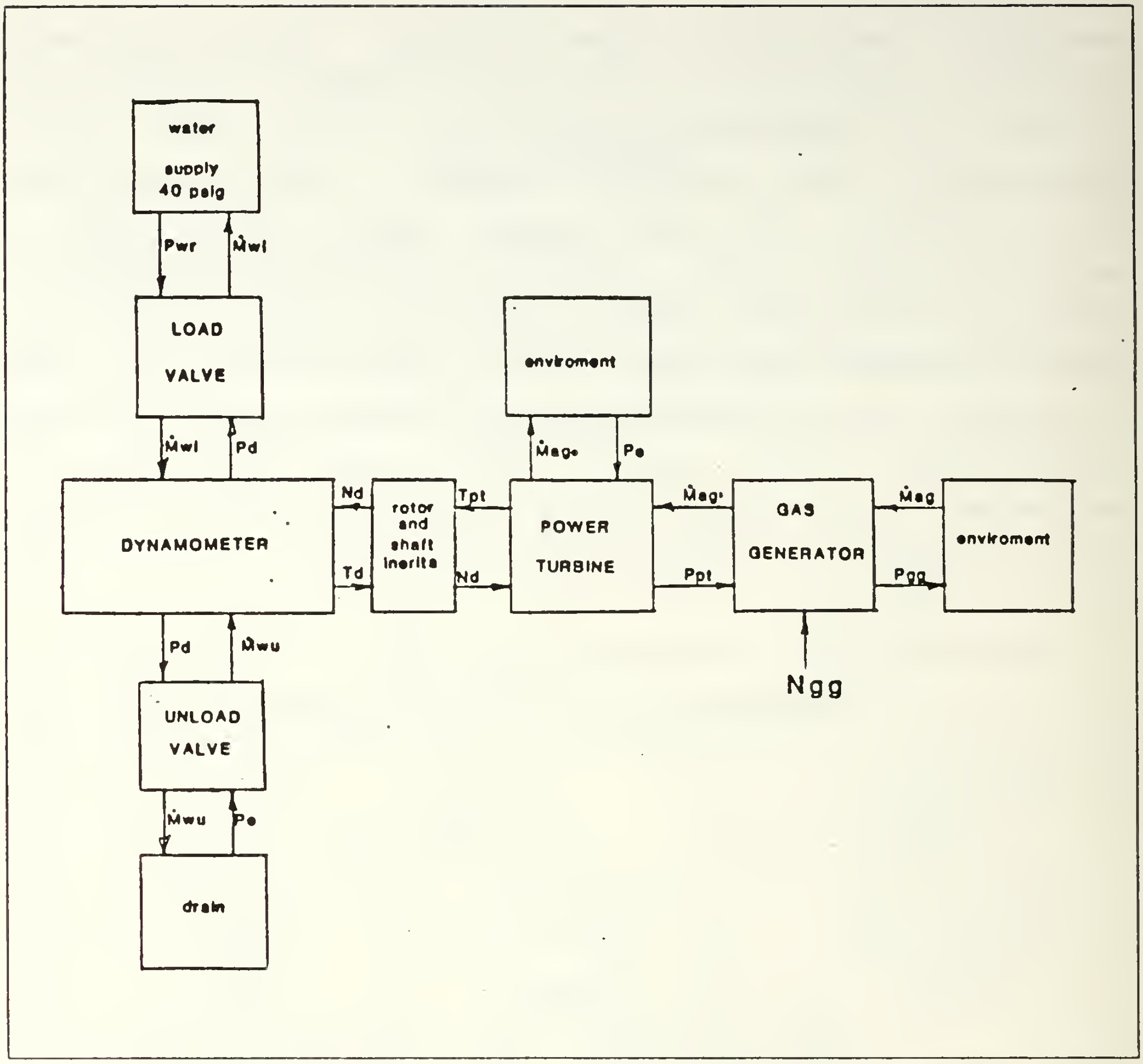

Figure 3.2 Unmodified Hardware Multiport Analysis.

dynamometer. At the onset of this work, two half inch solenoid valves provided for water addition or removal through a network of approximately 80 feet of copper tubing and flex hose. The power turbine and dynamometer were connected by a shaft which acted as a torque summing device, as shown in the Figure. The gas generator was controlled by a speed governor which regulated fuel flow to achieve gas generator speed selections. The load and unload valves were manually controlled to achieve desired shaft speed.

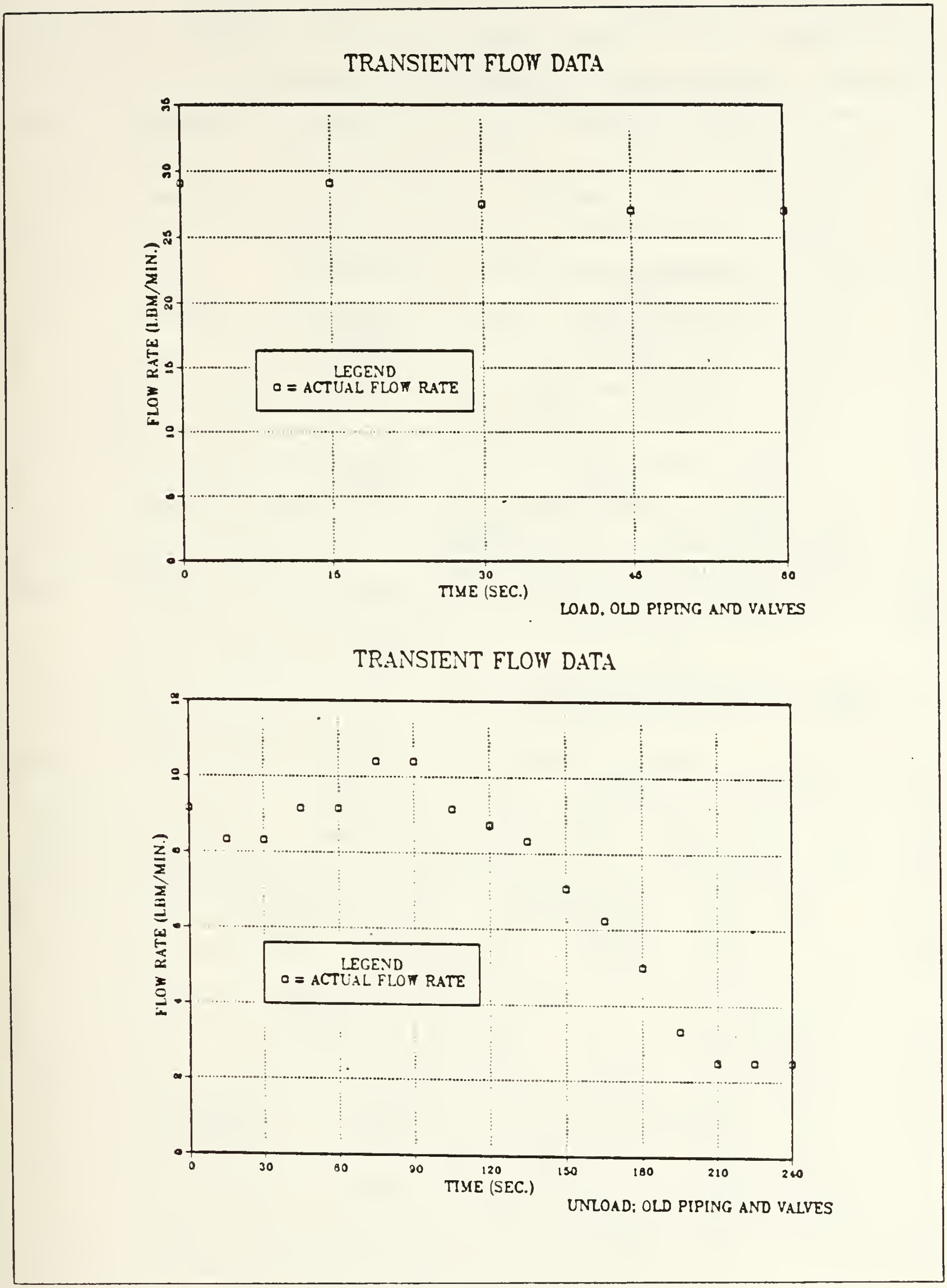

Figure 3.3 Solenoid Valve Flow Rates.

The evaluation of the solenoid valves operation is shown in Fig 3.3. The Figure shows that the dynamometer loading flow rate remained nearly constant through the load transient and could to be modelled as constant. However, unload flow rate varied widely. This droop in the unload flowrate was due to the large change in the valve up stream pressure (Pd) which was observed to vary between 0 and 10 psig, depending on dynamometer speed and loading. It was thought that the creation of a constant pressure chamber in the dynometer by the addition of a regulated air source would improve this droop in flow rate so that it too could be assumed as constant. Furthermore, in order to decrease the load transient time to meet specifications, the flow needed to be increased. This required increasing the pipe diameters and shortening the piping run. Also, proportional water flow control was required to meter the flow rate and hence control the dynamic transition of load states.

B. PLANT HARDWARE MODIFICATIONS

Figure 3.4 shows a multiport analysis of the modified system. Here, the supply and return water lines were shortened and increased to one inch in diameter. An air pressure regulator was added to the dynamometer shell which provided a four psig head pressure to the dynamometer unit during operation. These changes provided the capability necessary to remove the 15 lbs. of water in 15 seconds as called forth in the specifications for power dissipation. Proportional valves were also designed and added to moderate flow rates to and from the dynamometer. A control implementation of speed regulation was chosen over torque regulation because of the necessity to develope a speed regulator for lab requirements and because the signals were less noisy. Servovalve positioning was to be accomplished by valves

which were designed to attain their desired position independently of microprocessor control, i.e. , position based soley on an analog reference voltage, with internal regulation. This was to speed the control duty cycle.

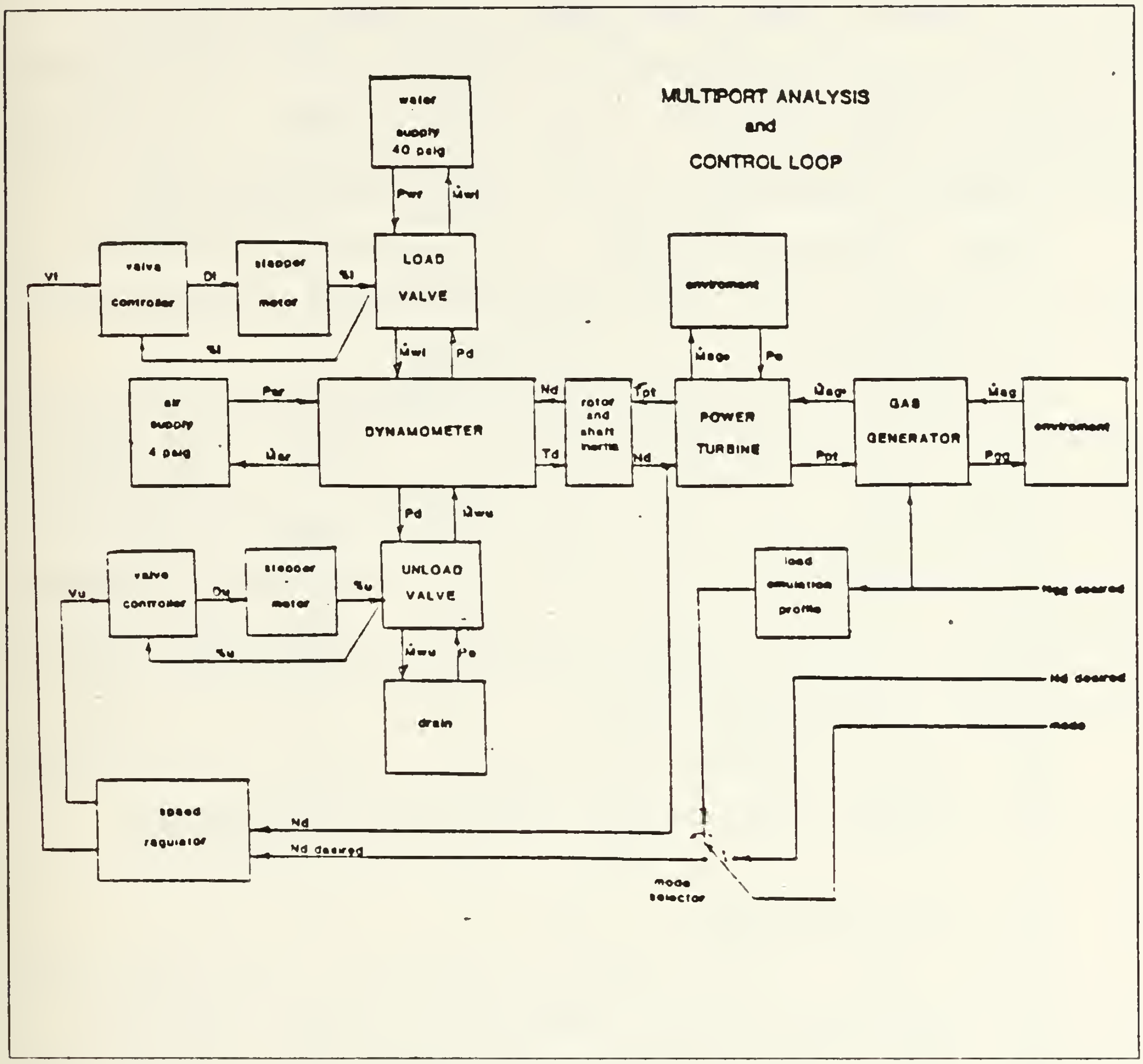

Figure 3.4 Modified Multiport Analysis.

C. PLANT MODELLING

In order to simulate the plant dynamics, the equations describing component behavior had to be developed. These equations described the torque absorbed by the dynamometer as a function of water weight and rotational speed, as well as the torque developed by the power turbine as a function of gas generator speed and power turbine speed. The dynamic effects were lumped into an inertia resistance of the drive train, gears, rotors and water volume in the dynamometer.

A least-squares technique was employed to develope a best fit equation for each of the respective components with the data collected.

The turbine rotor inertia was obtained from the turbine technical reference manual [Ref. 4]. Steady state turbine performance was collected from previous lab work performed by students enrolled in ME 3241 at the Naval Postgraduate School. Additional data was also collected to verify performance at lower operating speeds. Dynamometer rotor inertia was obtained directly from the manufacturer, as was steady state performance data.

Strip chart recorders were used to record transient data for time constant analyses and simulation comparisons.

D. OPEN LOOP SIMULATION

The open loop plant and valve dynamics were programmed into the Continuous System Modelling Program CSMP III to validate their accuracy by direct comparison to strip chart recordings.

E. CONTROL AND DATA PROCESSING HARDWARE SELECTION

The basic concept of propulsion emulation is shown in Figure 3.5. Here, a load emulation curve (A-B-C) is shown

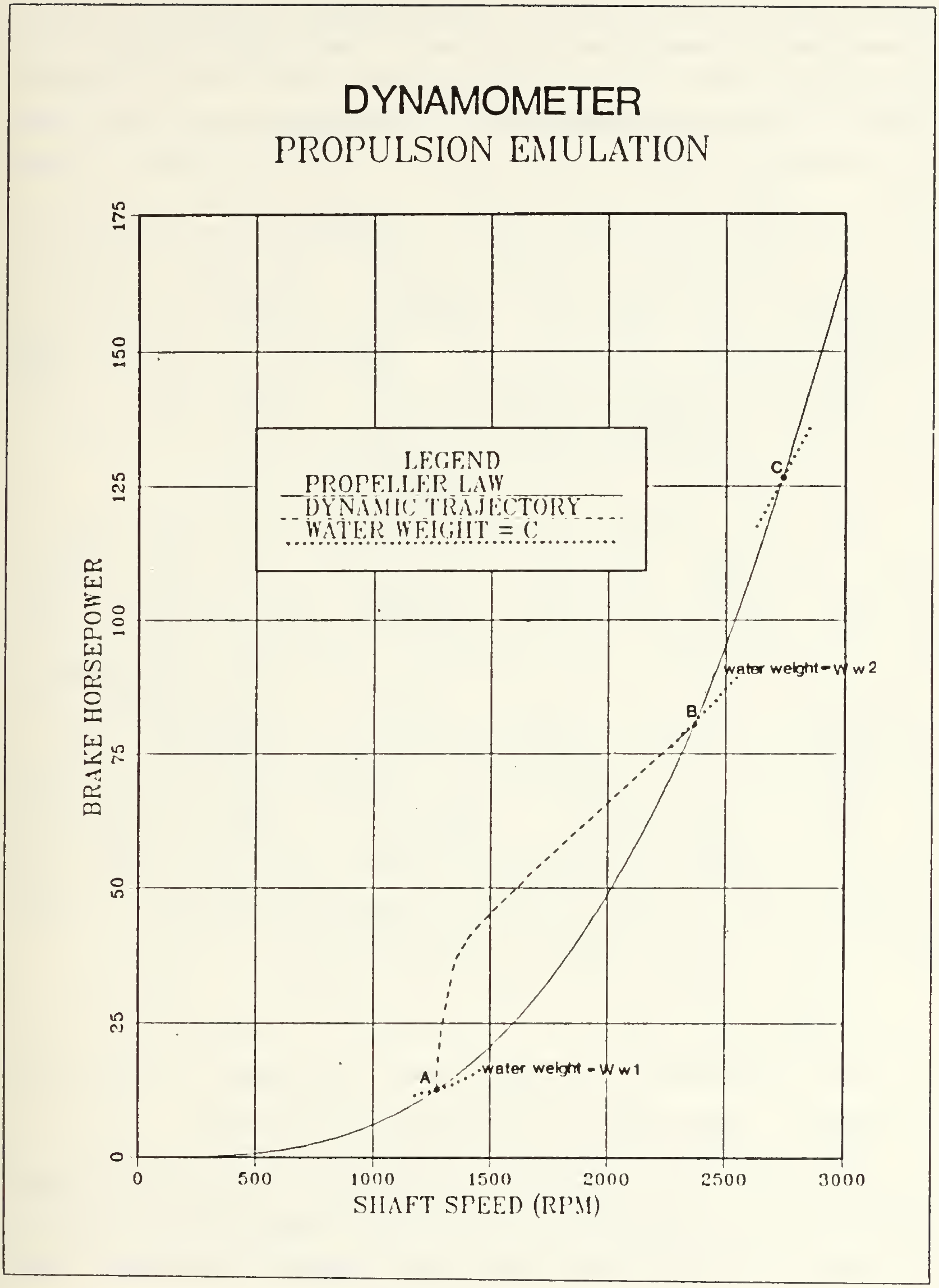

Figure 3.5 Propulsion Plant Emulation.

for a proposed emulator. The propulsion emulator sensed dynamomter and gas generator speed, and computed the torque generated by the power turbine, (point A). It then established a desired speed based on gas generator state along the propeller curve, (point B). For the purposes of this work, a cubic equation was used for the propeller law which passed through 165 horsepower at 3000 rpm and the origin. Having established a desired speed, the speed regulator manipulated the valves in order to transit to the new setpoint (dashed line A to B). Since the controller works by adding or removing water from the dynamometer, in this example the dynamometer went from water weight Ww1 to Ww2 as shown in the Figure for the transition of A to B.

Due to the need for flexibility in this and subsequent work, a microprocessor based approach was selected to implement the control algorithm. Reduction of the data from the operator panel and student instrument panel was also implemented in order to provide easier and more comprehensible results for laboratory work. However, since computer data aquisition transducers are particularly expensive, the use of dedicated transducers in the turbine test cell was found to be cost prohibitive. Therefore, a data acquisition system was implemented which provides the flexibility to be disconnected for use on other experiments and is simple enough to be easily setup at any location.

F. CONTROLLER DESIGN

The simulation tool CSMP III was used to design the controller (regulator) in a cut-and-try fashion.

The following guidelines were used in the selection of proportional, derivative, and integral controller gains. All gains were initially set to zero. The proportional gain was increased until an oscillitory condition existed, then

reduced slightly until a smooth transition to steady-state was achieved. The derivative gain was selected next to meet overshoot and transit time requirements. The integral gain was to be selected last to provide reset action in a reasonable period.

G. CONTROLLER PROGRAMMING

Several computer programs were required to implement computer aided aquisition and control of the dynamometer. The computer first sampled all input data sensors, then computed the correct control commands and finally output the commands. It was decided to perform this procedure on a fixed interval for simplicity.

The data acquisition system provided the necessary prompts and error checking for the user. The output listings included direct readings as well as a limited reduction of the data which was dissplayed in accordance with the specifications.

In this approach, it was decided to test Tiny Basic as a candidate control development language. If the computer-interpretted code for controller processing took longer than the 100 milliseconds as required by specification, then the controller would need to be programed in machine language since an assembler or compiler was not available. However, the Tiny Basic program testing revealed cycle times of 400 milliseconds. This was four times too slow for the anticipated requirements, therefore, in order to increase execution speed, control routines were programed in machine language. The task of converting a higher level language to machine language is best accomplished through the use of a compiler. A secondary approach is to use an assembler to develope the machine routines. The least efficient and most time comsuming method is to hand compile the routines and

program them directly into the microprocessor. However, because of budgetary and lead time restrictions the last and least desirable method was utilized. Each Basic line was individually broken down into machine language and sequentially programed into memory. Because there was no assembler or compiler, monitoring detection and correction of errors was difficult.

IV. RESULTS

A. PLANT HARDWARE SETPOINTS

The dynamometer's steady state performance could be changed substantially by the adjustment of an internal flow control valve integral to the heat exchanger (see Figure 4.1 and 4.2). The dynamometer technical reference manual

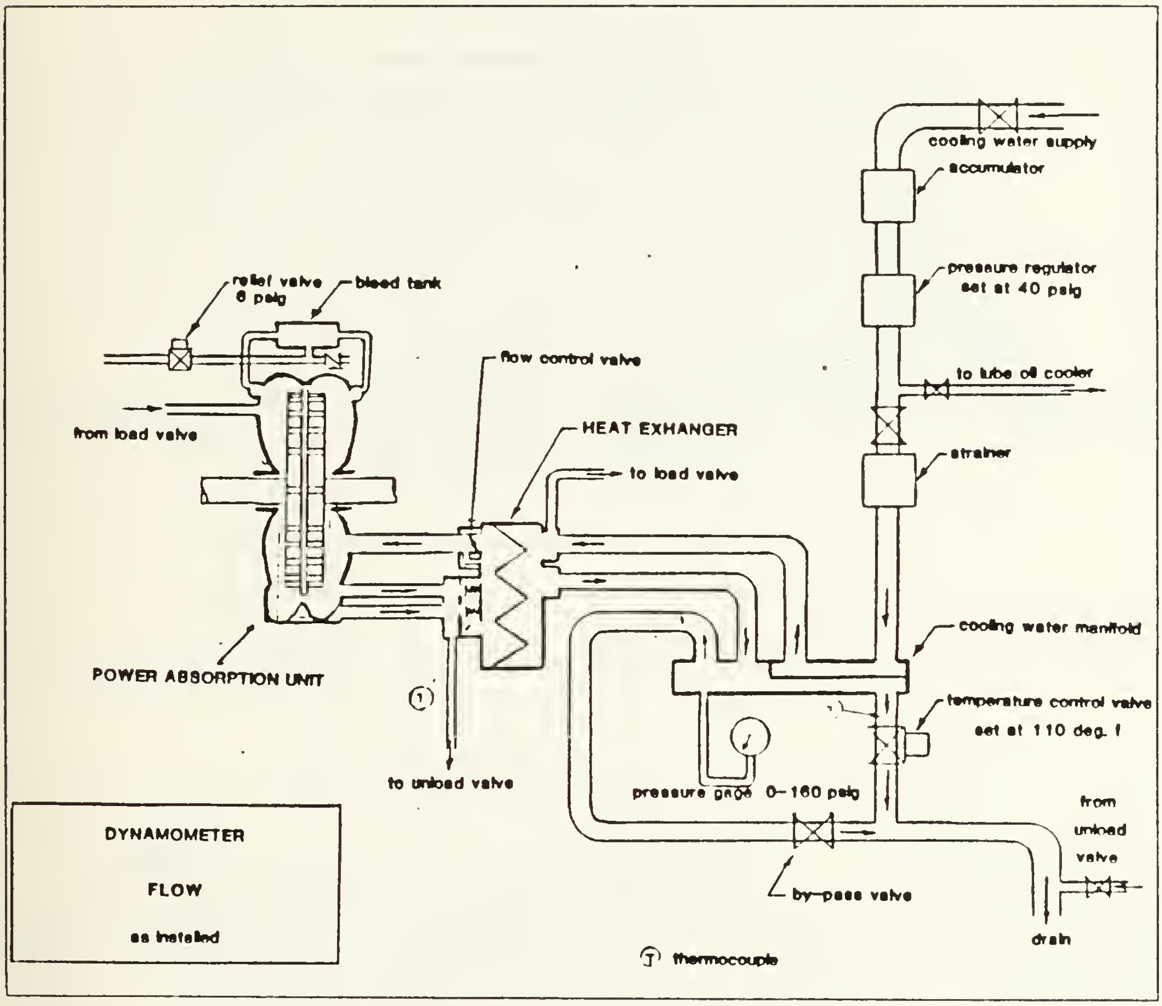

Figure 4.1 Unmodified Dynamometer Flow.

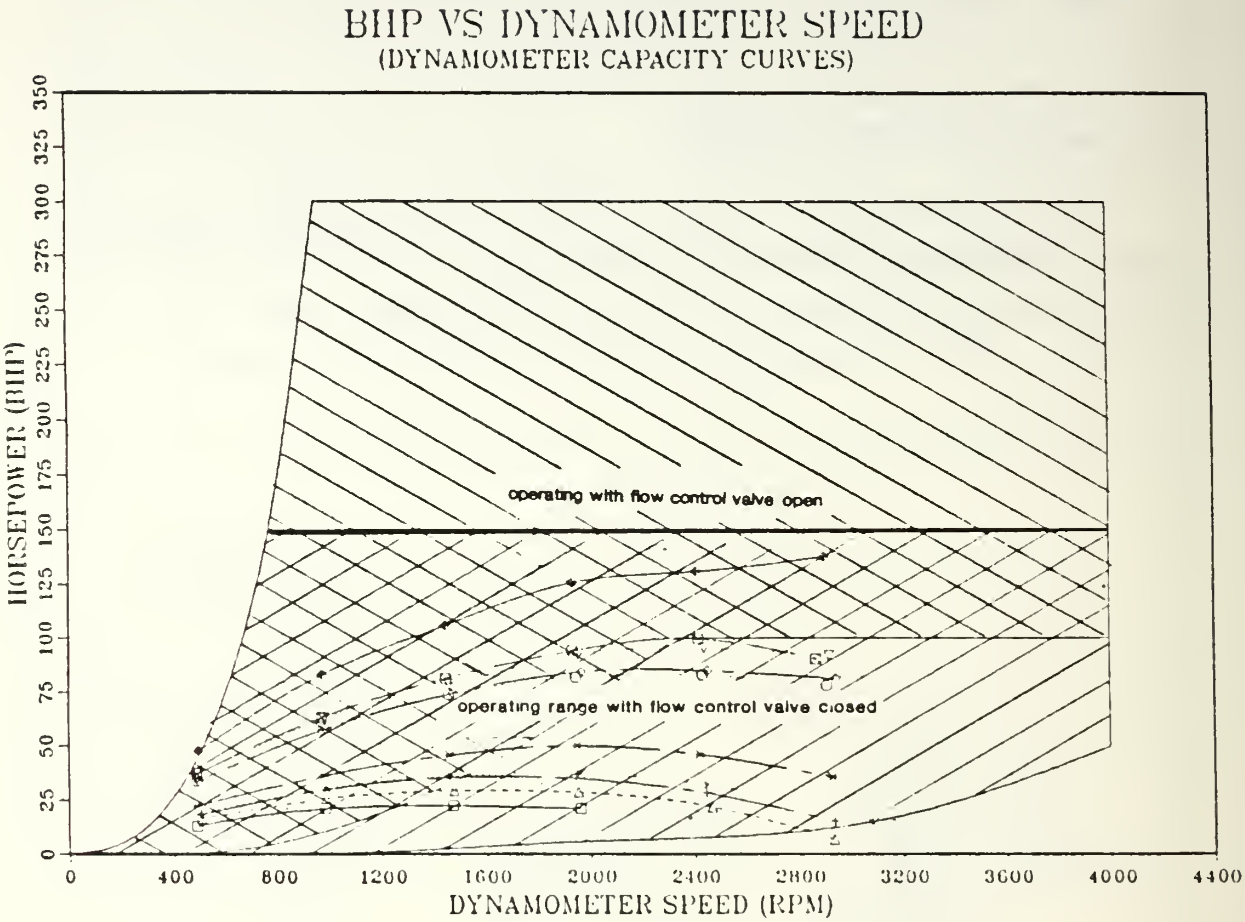

Figure 4.2 Original Dynamometer Load Flow and Control.

[Ref. 5] indicated that this valve is used to control stability at light loading. It is important to note that the dynamometer power absorption unit is capable of absorbing up to 750 horsepower when provided with two heat exchangers but, as currently configured, a limit of 300 horsepower is mandated. The flow control valve must be in the open position while operating above 150 horsepower in order to provide adequate cooling, but this provides instability at light loads. Thus, as a compromise, the flow

control valve was set at 25 percent open and left there for all subsequent work.

Dynamometer temperature was also monitored during runs and ranged between 90 and 120 deg f. when regulated by a constant temperature regulator set at 110 deg f. It should be noted that dynamometer water weights between .5 lbm. and 48 lbm. define the limits of operation and that lab usage often requires use of this full range.

B. PLANT MODELLING

Inertia data was collected by subjecting the dynamometer and power turbine to a near constant torque as provided by operator and gas generator throttle position, and measuring the speed signal with a strip chart recorder. The acceleration was estimated from the speed trace and the inertia was calculated from equation 4.1 below. The sum of manufacturers inertias of 1.8 lb-ft-sec^2 for the turbine and 14.81 lb-ft-sec^2 for the dynamometer agrees closely with 16.7 lb-ft-sec^2 experienced during acceleration runs. The water volume inertia seemed to have little effect as evidenced by accelerations performed at various degrees of loading. The negligible difference between the manufacturers and experimental inertias was attributed to additional inertias of shaft and universals which couple the dynanometer and power turbine.

$$It = Td / \dot{N}d \qquad \text{(eqn 4.1)}$$

The relationship between dynamometer water weight and dynamometer torque and speed was also needed as part of this study. This data was collected by measuring torques and speeds at various gas generator speeds with a constant water volume. The water weight was measured at the conclusion of

each experiment by draining the dynamometer. A total of six runs with 28 data points each were obtained and are shown in Figure 4.3 The dynamometer manufacturer supplied additional information which agrees with data collected.

The steady state turbine data was obtained from runs performed by students enrolled in ME 3241. In addition, data was also taken at compressor speeds below 27000 rpm in order to completely map the power turbine performance. During this work, the gas generator was assumed to have a perfect regulator. Thus, once Ngg was selected it was assumed to remain constant during all dynamometer transients. This asumption was validated through data recordings of Ngg. While the shape of the curves for power turbine torque output agree qualitatively with those from the manufacturer, our results are somewhat less in magnitude. This was attributed to the thirty years of turbine usage since installation at the Naval Postgraduate School. The equation is plotted in Figure 4.4.

A least-squares technique was employed to develope equations which represent the data obtained. For the dynamommeter, the torque absorbed was assumed to be a function of water weight and input speed (rpm) and is shown in equation 4.2. The power turbine steady state output torque was assumed to be a function of power turbine output speed and gas generator speed as shown in equation 4.3.

$$Td = -20+((0.00046*(Ww/16.6)**1.3)+4.0E-6)*(Nd**2) \qquad \text{(eqn 4.2)}$$

$$\begin{aligned} Tpt = (-725.76+(0.0363642*Ngg))+(0.05267138 \\ -(4.454586E-6*Ngg))*Nd \end{aligned} \qquad \text{(eqn 4.3)}$$

These two equations were the result of a trial and error procedure of investigating various unsuccessful function forms for dynamometer and power turbine torque. The unsuccessful candidates are shown in equations 4.4 to 4.8.

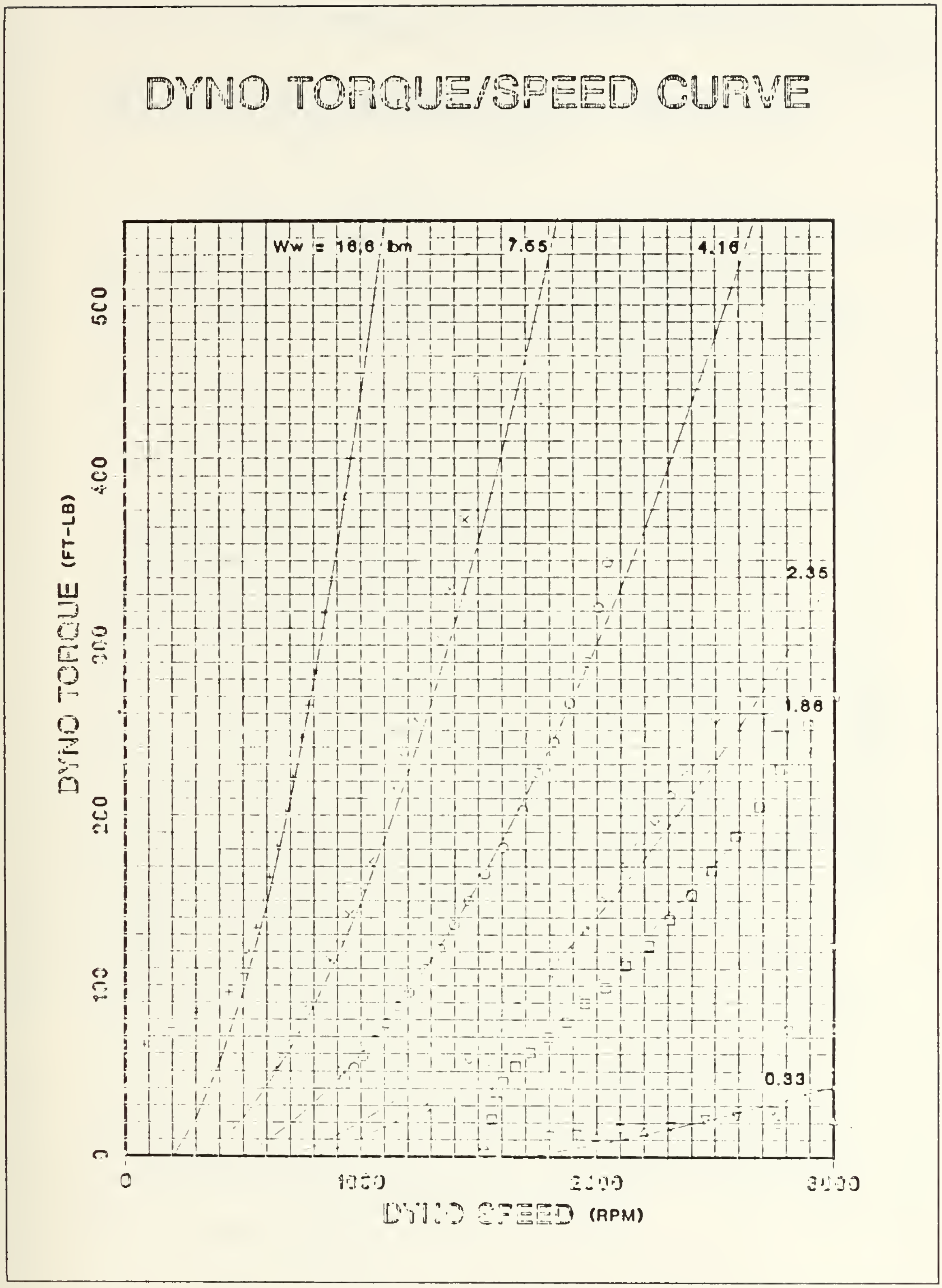

Figure 4.3 Dynamometer Capacity Curves.

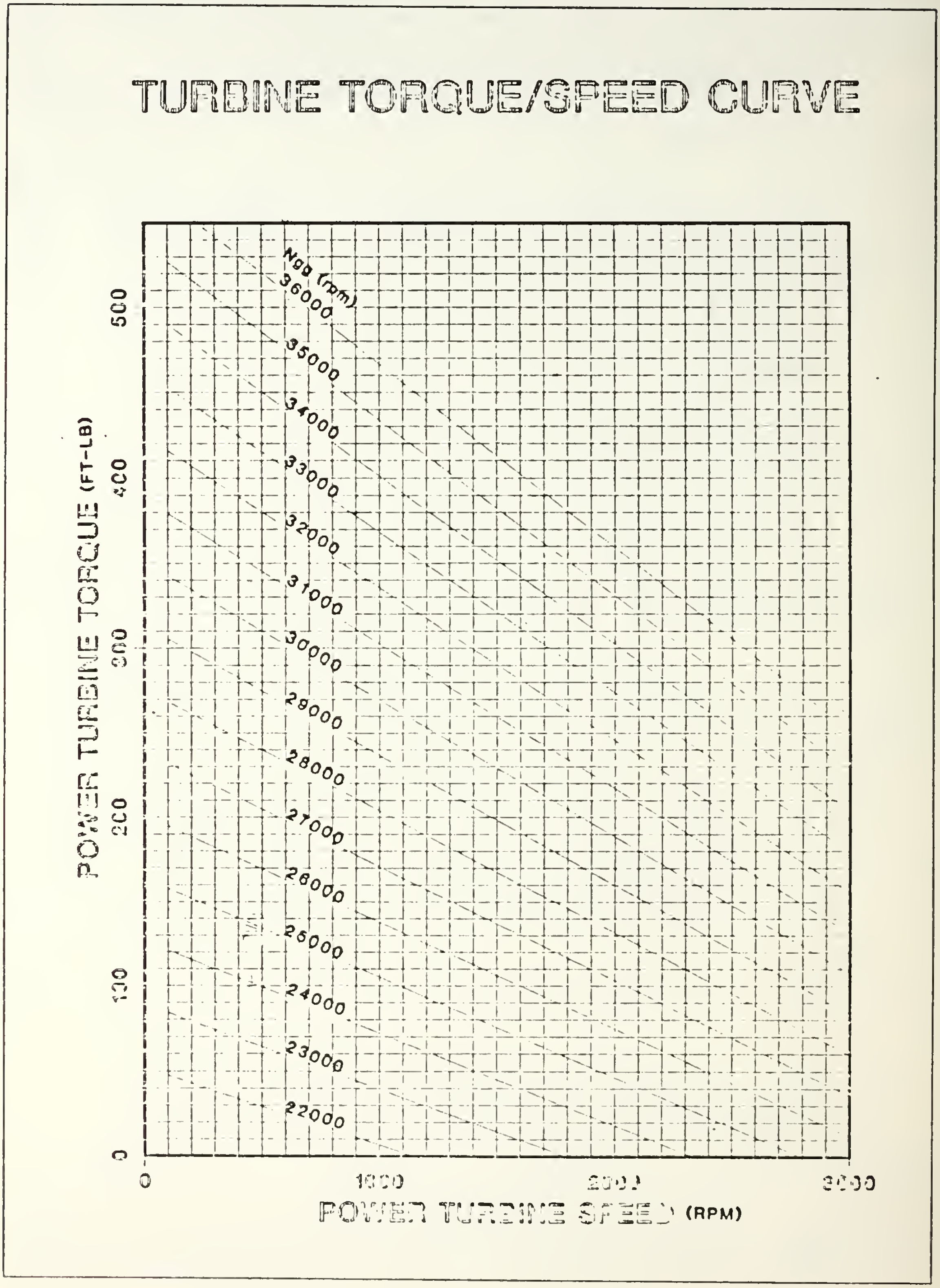

Figure 4.4 Turbine Torque Speed Performance.

```
...00046*((0.10+(Ww/18.5)))**1.5))*(Nd**2))                    ...)-205
                                                                 (eq
Td = (((1.25293E-7)*Ww**3)-((1.35816E-6)*Ww**2)+((5.61E-6
     *Ww)*(-6.176477E-6))*((Nd)**(2.64718-((
     3.603287E-2)*Ww)))                                          (eqn
Tpt = (Ngg-18666.0)/33.3-0.0816*Nd                               (eqn 4
Tpt = (-412.97+(0.029*Ngg))+(0.052671-(4.4586E-6*Ngg))*Nd        (eqn 4.
                                                                 (eqn 4.8
```

The steady-state turbine and dynamometer data was use as a model for both the static and dynamic states o performance of those units. All inertias were lumped into the rotor model and the acceleration was based on equation 4.9.

$$Nd = (1/It)*(Tpt-Td) \qquad \text{(eqn 4.9)}$$

C. OPEN LOOP SIMULATION

The unmodified plant was simulated to validate the dynamometer-inertia-turbine model. The equations developed from dynamic and steady state modelling were used to simulate the system dynamics via CSMP III. The model was subjected to similar transients as those recorded in the data collection phase, which is shown in Figure 4.5. The simulation for dynamometer loading Figure 4.5 (top) shows good agreement over the normal operating ranges of the equipment. However, unloading results were quite different, Figure 4.5 (bottom). This difference was due to the poor model of unload valve fluid dynamics. Actually, when the dynamometer was unloaded, initial water flow rates were high, therefore the actual dynamometer unloaded faster than the simulation. As the real dynamometer approached 3000 rpm

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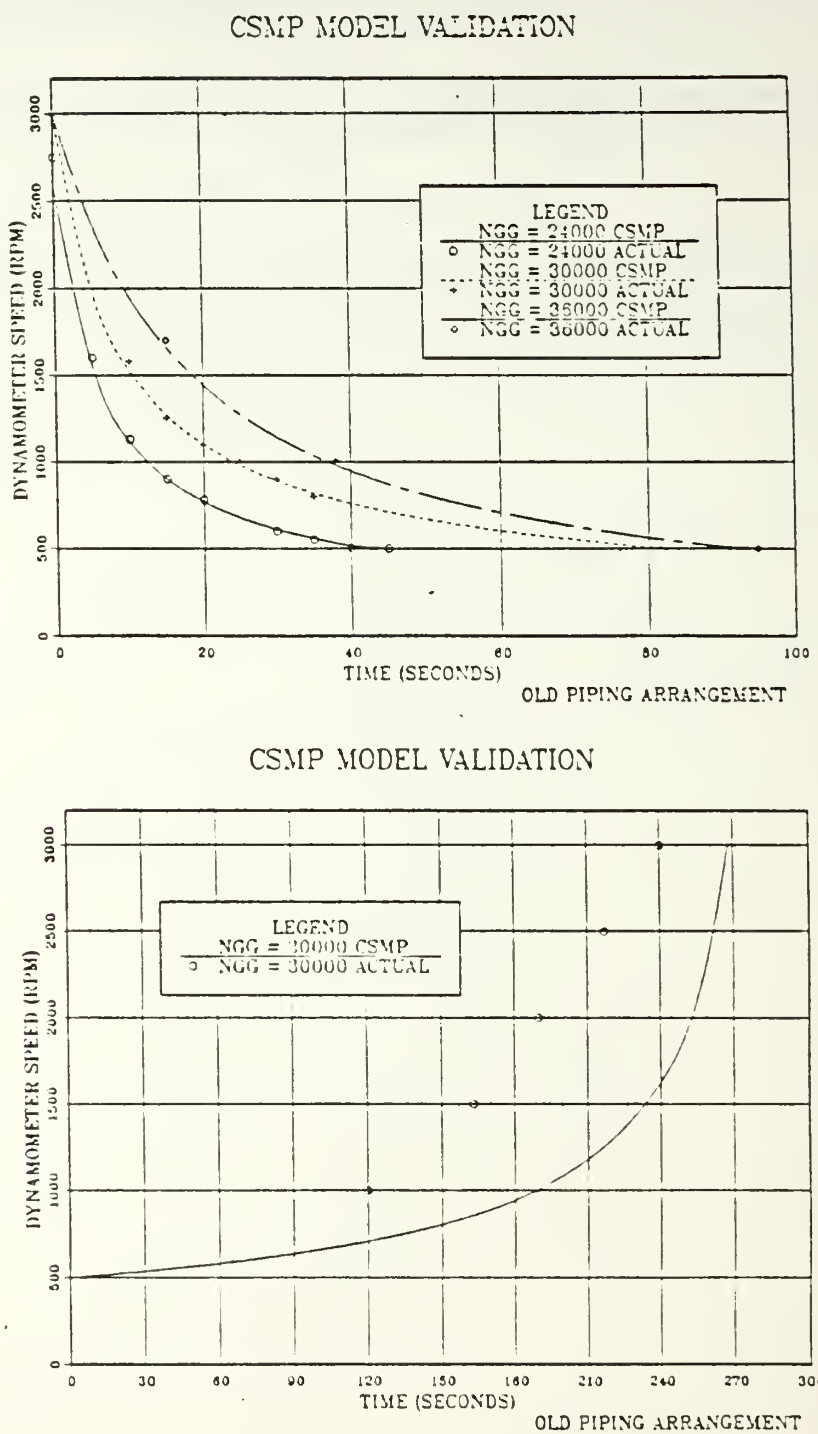

Figure 4.5 Open Loop Simulation.

the flow rate was less than the model and it approached slower than the simulation. However, since unload flow was substantially less than the load flow rate and the dynamometer was to be modified with a constant pressure regulator, it was decided that the assumption of constant pressure drop across the valves could be maintained and control development could proceed.

D. CONTROL AND DATA PROCESSING HARDWARE IMPLEMENTATION

Governed by the need to provide an 85 percent load change in fifteen seconds, and knowing the volume of water necessary to provide changes in operating points, the valve and pipes were sized as discussed earlier (section III.B). The pipe and valve sizes were chosen to provide proper loading capacity to prevent overspeed of drive train if subjected to maximum acceleration of the gas generator. The load and unload sizes were chosen to be the same for simplicity.

In order to keep overall pipe size small and to provide a more constant pressure differential across the unload valve, an air pressure regulator was installed to maintain dynamometer shell pressure at a constant 4 psig (Figure 4.6). The piping modification also required an increase in water supply and removal capability. For the load system, water was tapped from the cooling supply header. Since the header and supply were designed for 750 horsepower operation, their capacity was sufficient to handle the needed load water. Additional water was supplied through the ports normally used to empty an additional heat exchanger. Because of the increase in filling capacity, an additional 1 inch relief valve was installed whose relieving pressure was approximately 8 psig.

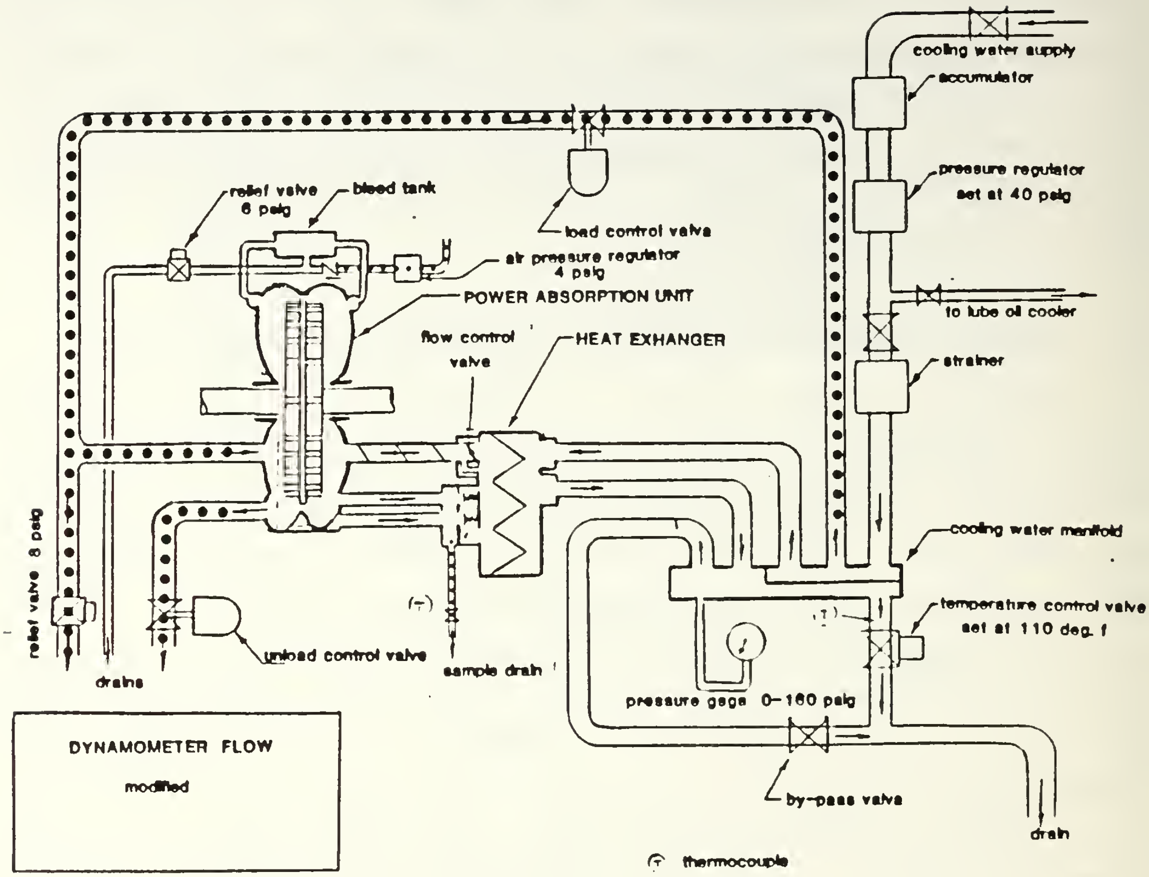

Figure 4.6 Modified Dynamometer Flow.

For the unload system, the water was extracted from the unused heat exchanger supply ports. This location is virtually the same as in the old conFiguration, however, it offers a much greater capacity. The unload water was then dumped into the same drain as the heat exchanger cooling water. Flexible hoses were used to pipe to the dynamometer to avoid torque shunts from the dynamometer shell to the test cell foundation.

Globe valves were selected to control the various flow rates required during loading and unloading operations. The required time constants of the valves were estimated to be approximately 3 seconds. These valves were designed to position independently of microprocessor control (i.e., position based solely on an analog voltage and internal regulation). A review of currently available electrically operated analog positioning valves revealed that none were available at a reasonable cost.

The design of the motor-actuated analog-voltage controlled valves started with the use of standard 1 inch brass globe valves. The number of revolutions as well as torque required to open and close the valve under pressure was determined. Motor selection was based on a torque requirement of 600 inch lbs. and a speed of approximately 40 rpm. A gear head motor was desirable, however, a slow synchronous motor was selected due to cost considerations. The use of a synchronous 72 rpm motor provided an interesting control problem in itself and is discussed in appendix E. The use of slow sync motors provided constant opening and closing rate. These motors had good torque characteristics and provided a time constant of 2 seconds.

Flow characteristics of the valves were measured using the on site water supply regulator for the load valve and a constant upstream pressure for unload valve. The result of transient and capacity testing is shown in Figure 4.7. The load and unload valves had similar characteristics under these conditions.

Microprocessor control was selected to provide the ease of modification needed for future work, and twelve bit input and output analog resolution was selected to provide smooth operation. Because analog output was required for valves and throttle positioning, a digital-to-analog interface board had to be designed. The details of this interface design are included as Appendix F.

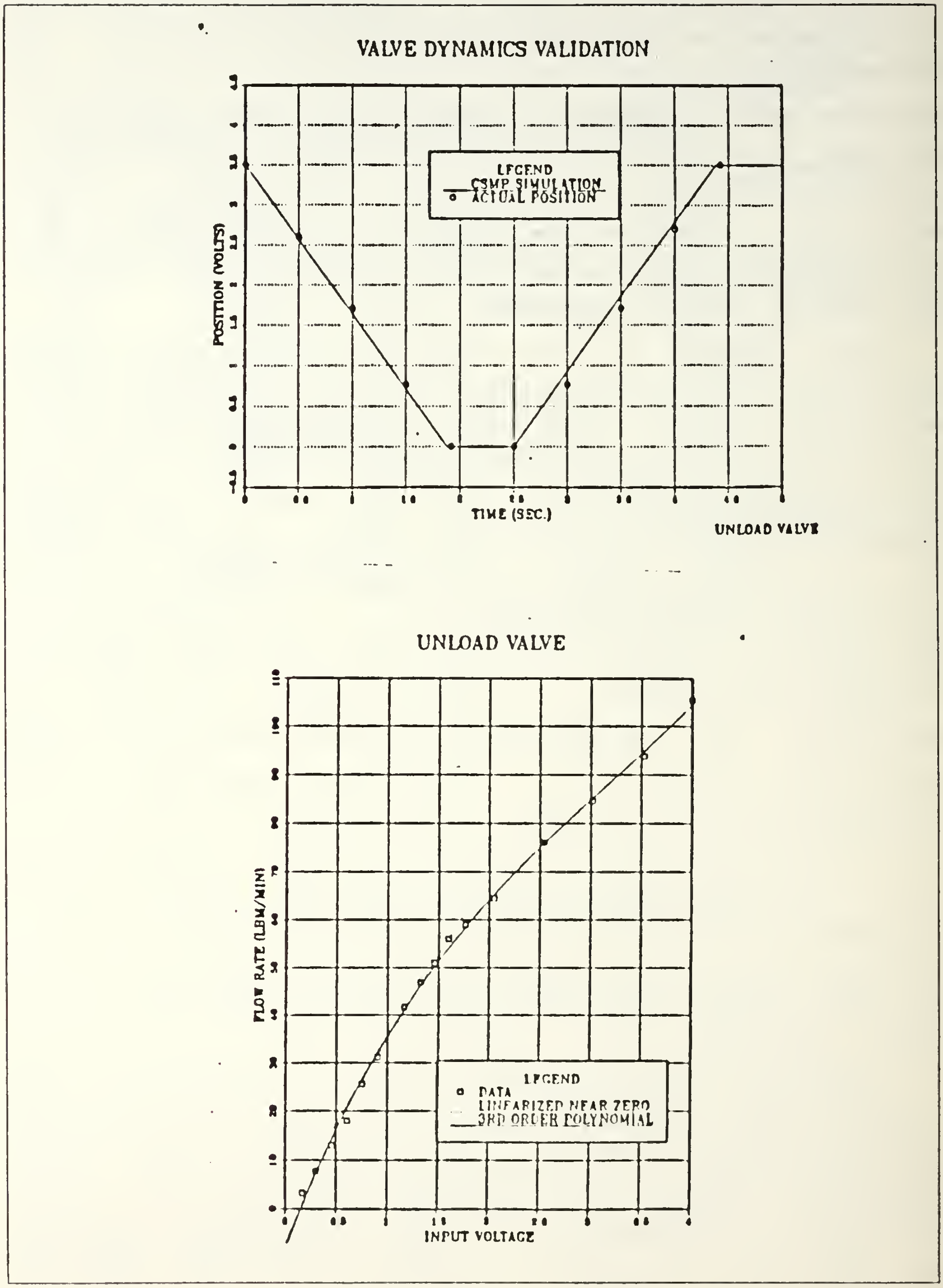

Figure 4.7 Load Valve Characteristics.

System modifications are shown in the following series of photographs. The first photograph Figure 4.8 shows the turbine test cell. On the left the side is the observation window, in the foreground is the gas turbine, and behind it the dynamometer.

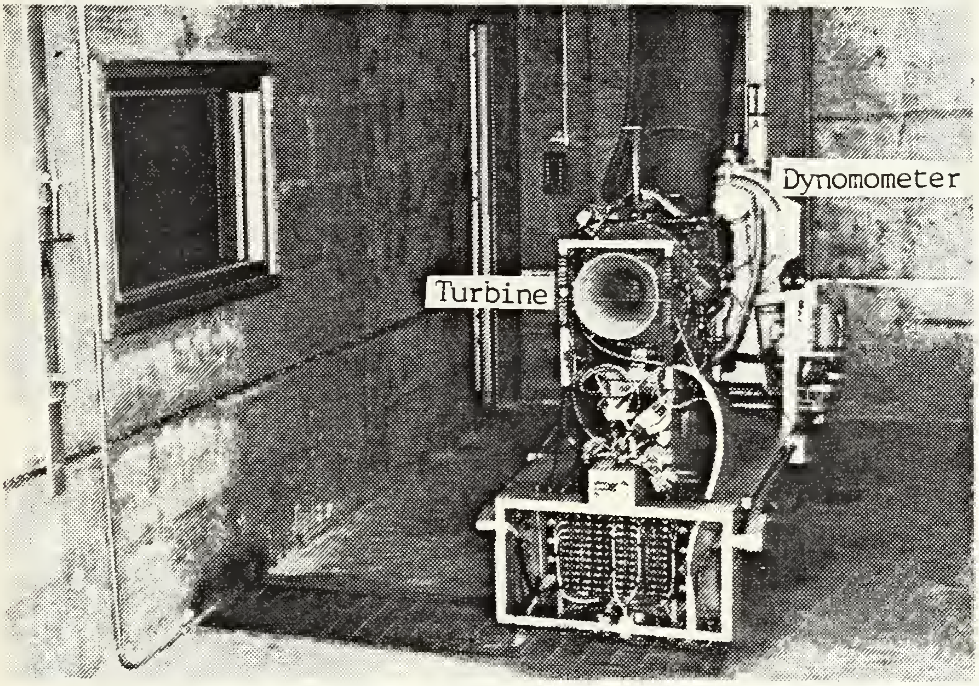

Figure 4.8 Photograph of Turbine Test Cell.

Figure 4.9 (top) shows the observation area. Here the test cell is located behind the wall at the left. The operators station is located against that wall and faces the observation window. The student instrument pannel is located against the far wall, and on the right is the computer data aquisition system. The photograph in Figure 4.9 (bottom) provides a closeup view of the data acquisition

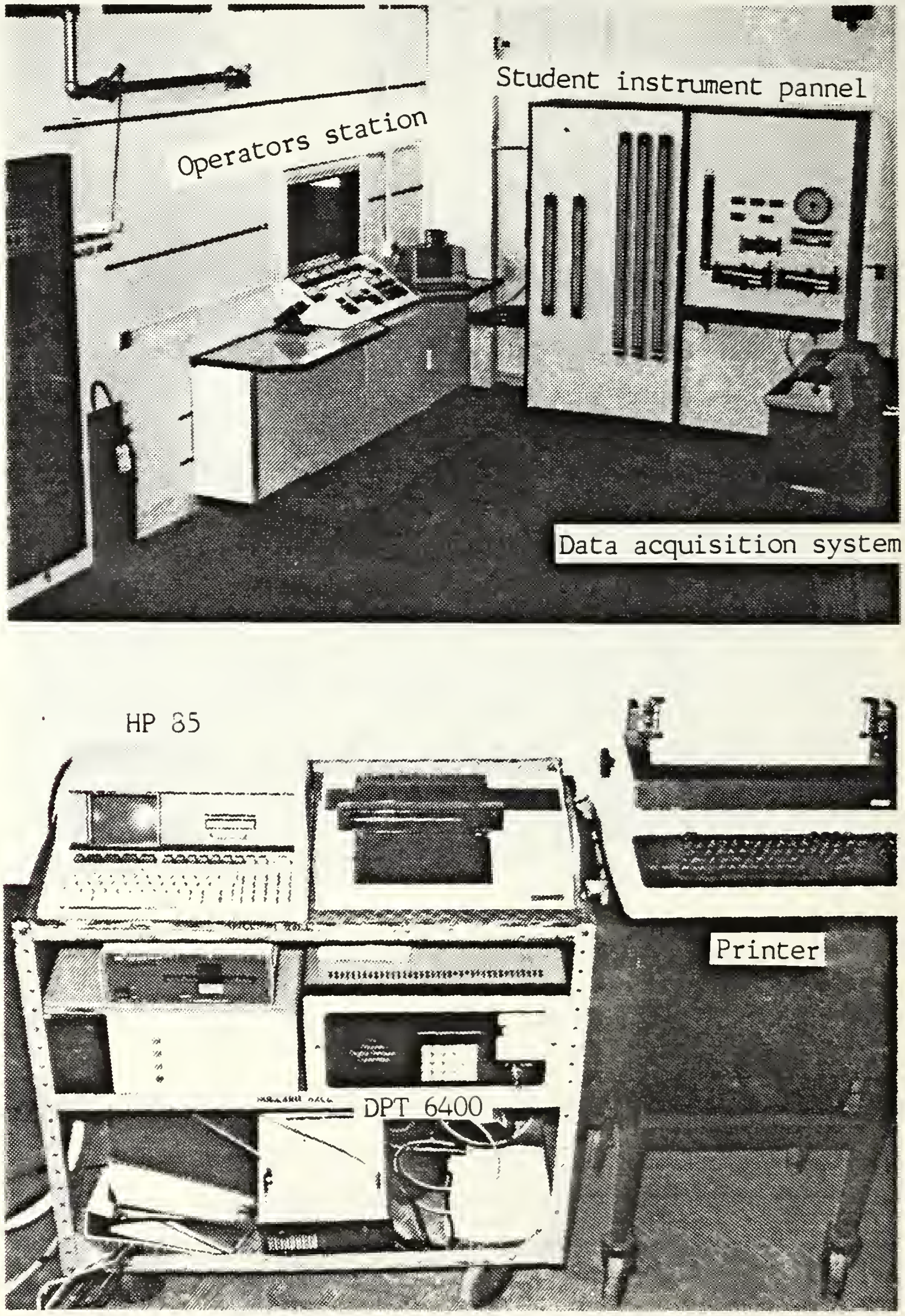

Figure 4.9 Observation Area and Acquisition System.

system. The HP 85 which controls the acquisition equipment, is located on the top left side of the photograph. Below the computer is the disk drive which provides storage capability. Below the disk drive is the HP 9741 used to convert speeds and temperatures into digital information for the HP 85. To the right of the HP9741 is a DPT 6400 which senses pressures for the Hp 85. A printer and plotter are located to the far right.

Figure 4.10 (left) is a rear view of the dynamometer. In this photograph, the water supply system is in the lower left corner. Just above and to the right of the inlet lines is the air pressure regulator which maintains constant shell pressure. A shell pressure gage which is affixed to the top of the power absorption unit for the operators viewing. Attached to the side of the power absorption unit is the load cell. Just below and to the left is the drain valve used to collect water volume samples. Behind the drain valve is the heat exchanger whose discharge piping can be seen exiting near the water supply lines.

Figure 4.10 (right) is a front view of the dynamometer. On the left is the rear section of the power turbine. To the right is the shafting and dynamic torque sensor and the dynamometer power absorpition unit. Below the absorption unit is the valve positioners,valves and piping.

Figure 4.11 shows a closeup view of the one inch globe valves and stepper motors. Here the details of how the motor is mounted to the frame are shown, as well as the three to one gear set that drives a ten turn potentiometer for position sensing. A spline arrangement was designed to act just above the valve wheel which permits axial valve travel.

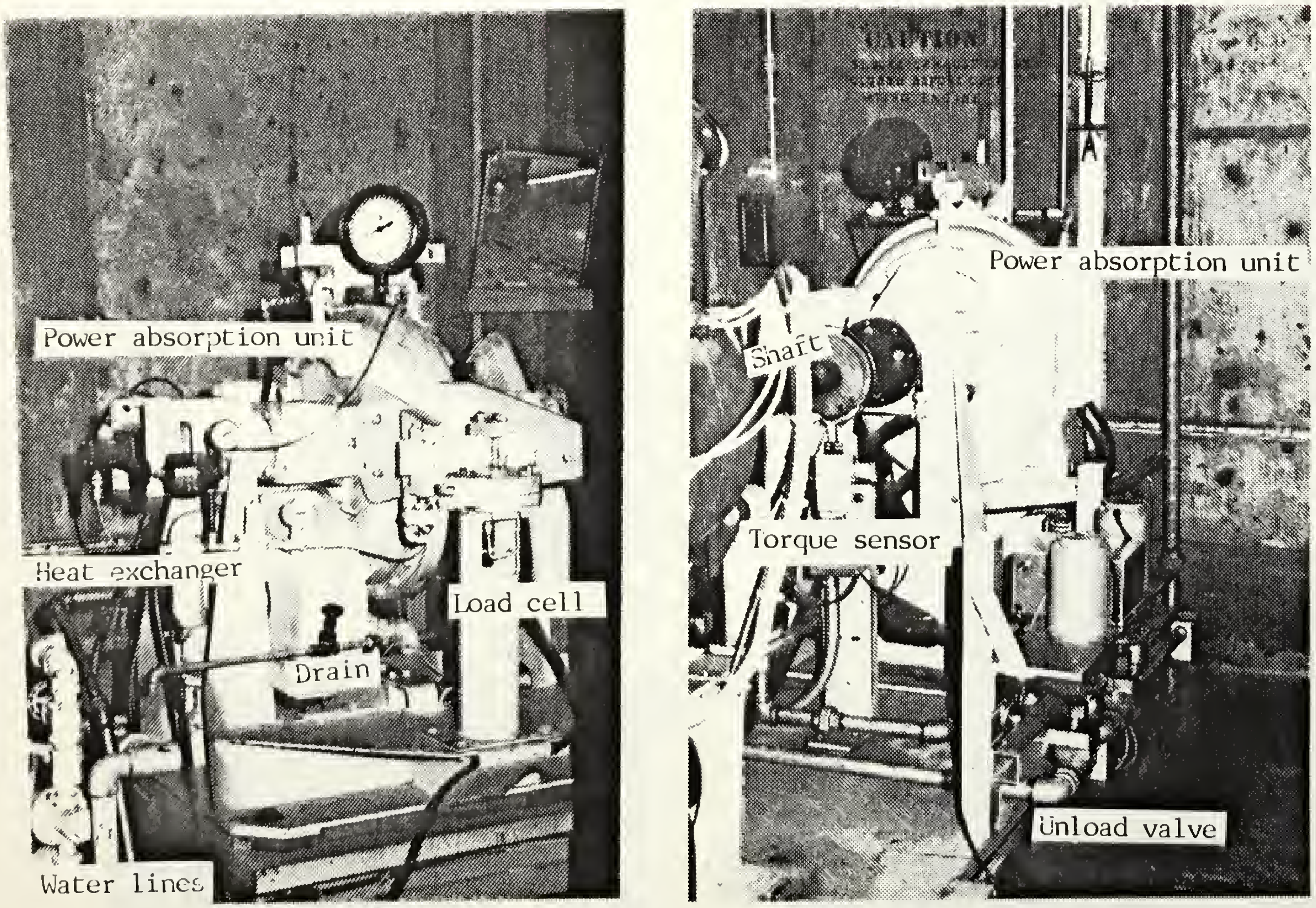

Figure 4.10 Front and Rear Views of Dynamometer.

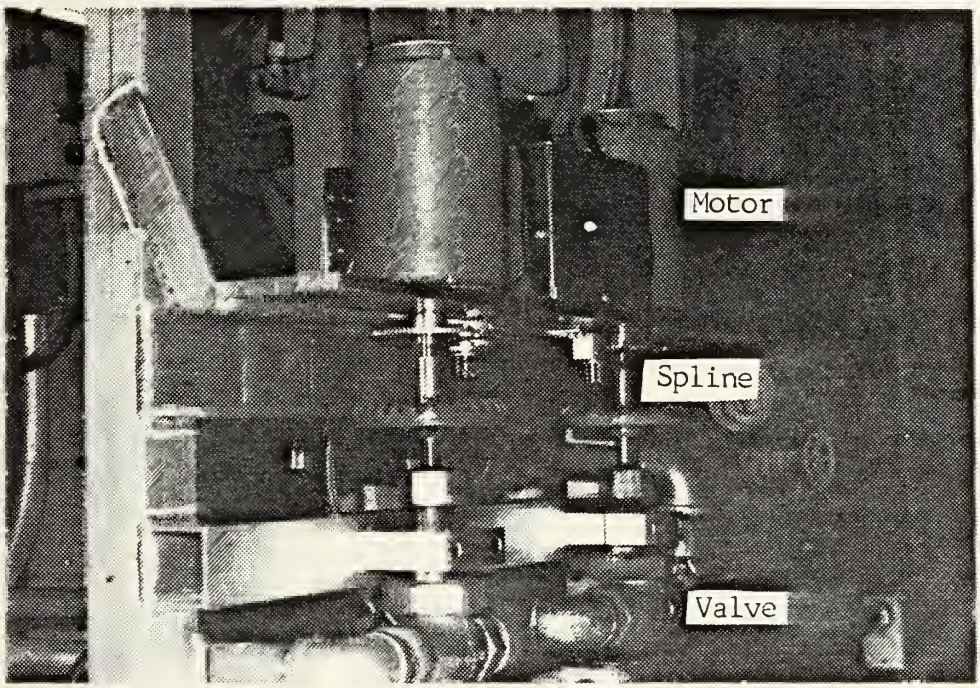

Figure 4.11 Closeup View of Valves and Positioner.

E. CONTROLLER DESIGN

The overall system simulation is shown in Figure 4.12. The Figure shows the three major system components. The block for plant open loop dynamics contains all the transient and steady state properties of the plant. The valve model block contains the transfer functions necessary to convert the controller output voltages into flow rate to the dynamometer, including the dynamics of valve positioning. The controller block simulates a digital type controller with fixed sample intervals and adjustable proportional, integral and derivative gains.

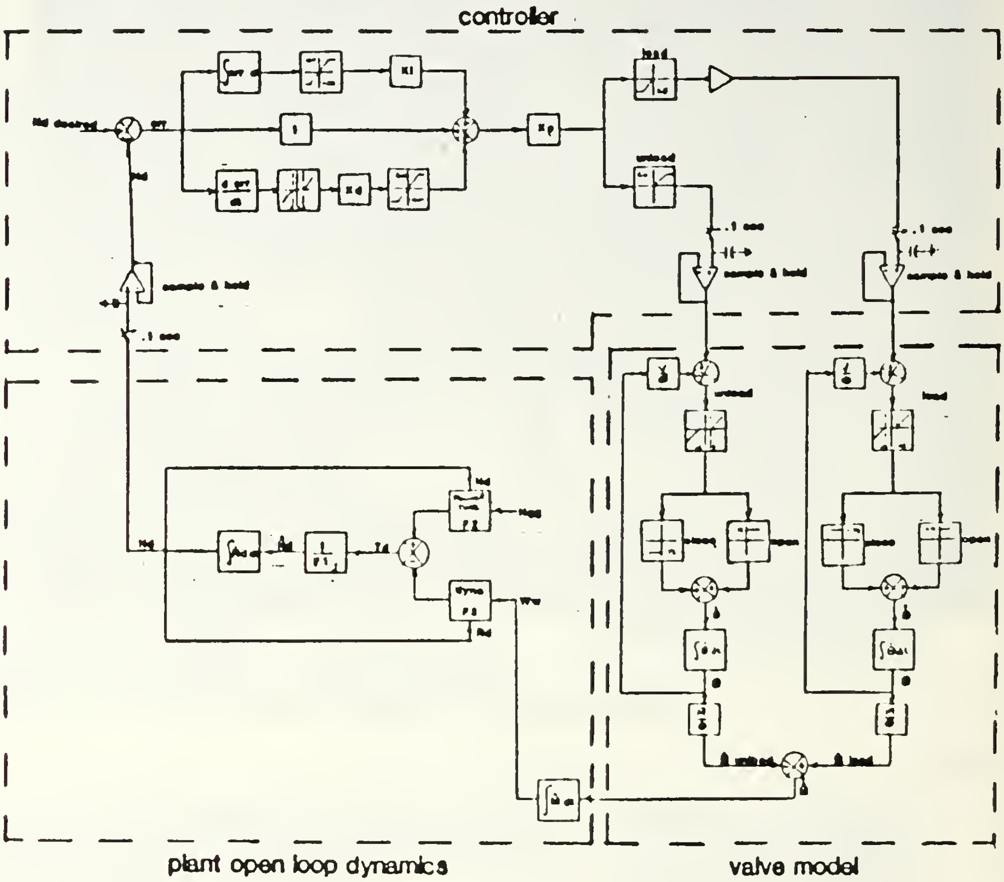

Figure 4.12 Block Diagram of System Simulation.

The use of a microprocessor controller introduced additional complexity to both the system model and the control algorithm design. Because the sampled signals were digitized, their derivative became very noisy at either very high or very low rates of signal change. Furthermore,

because this noise was most noticeable at or near setpoint where it has little value in the control solution, it was filtered out by elimination of all derivative values below and above thresholds. The integrated error signal was observed to saturate the controller when the system was subjected to step changes in demand. In order to compensate for this effect, maximum integral limits were established as shown in Figure 4.12.

The valves were tested in order to obtain a transfer function which related input voltage signal to output flow-rate. The valve dynamics analysis assumed that the synchronous motors would transit at a constant speed. This assumption was based on the fact that the torque of the motors was relatively high compared to the inertia of the valve and rotor. Verification of valve dynamics with actual transient data proved this assumption to be accurate enough for this study (Figure 4.7).

As mentioned above the predicted valve performance was based upon the assumption of constant shell pressure of 4 psig. The error of this assumpition is shown in Figure 4.13 where the closed-loop simulation and actual data are over-layed. Note that loading transients, where pressure drops across the valve are nearly constant, produce good aggreement with the simulation, Figure 4.13 (top). Unloading at low speeds and high torques, where shell pressures were higher than modelled, lead to speed increases which are faster than simulated (Figure 4.13, bottom).

The most arduous control scenario observed was used as the test case for controller development. This transient occursed at constant gas generator speed. It started at 500 rpm with the dynamometer fully loaded and required the rapid emptying of the dynamometer to attain 3000 rpm, where speed regulation was the most sensitive to water volume changes (similar to Figure 4.13 bottom). Later, after gains were

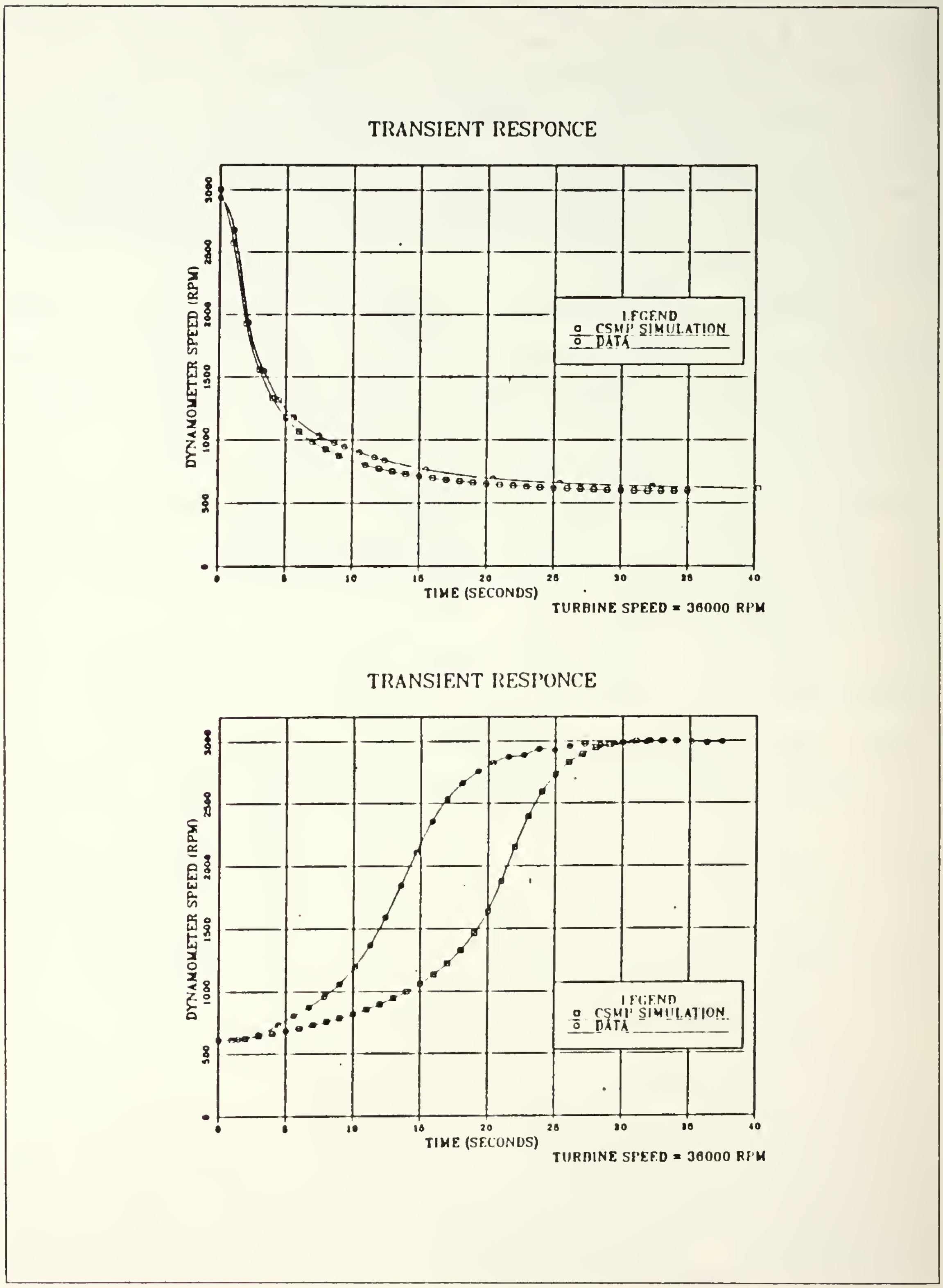

Figure 4.13 Close Loop Simulation.

selected, other transients were investigated to verify control over the full range of operation.

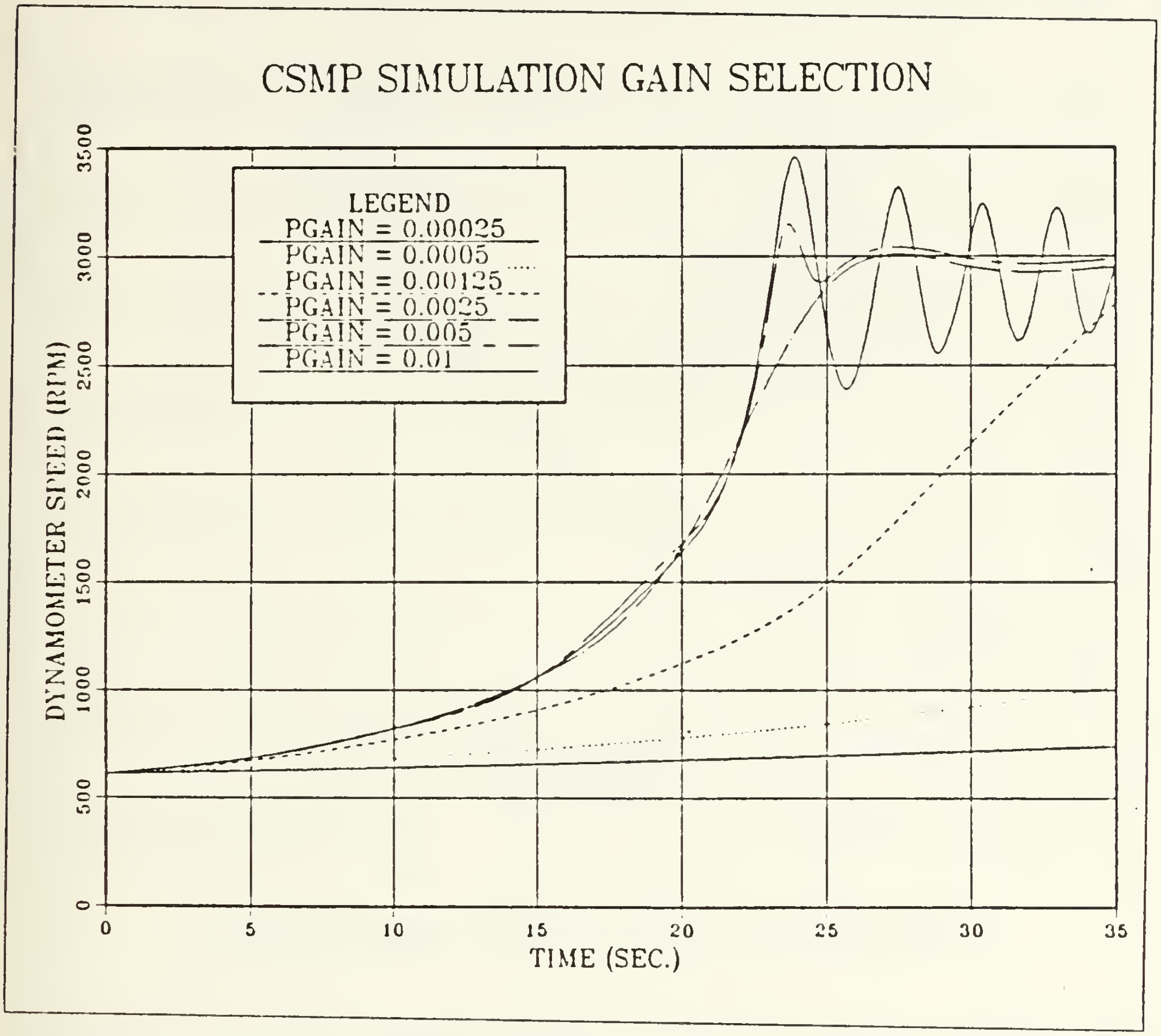

Figure 4.14 Proportional Gain Selection.

The selection of gains followed the guidelines discussed earlier. The proportional gains selection is shown in Figure 4.14. Note that for the first half of the transient, several of the the control solutions with different gains are overlayed on each other. This indicates saturation of the unload valve. Also shown is the effect that high

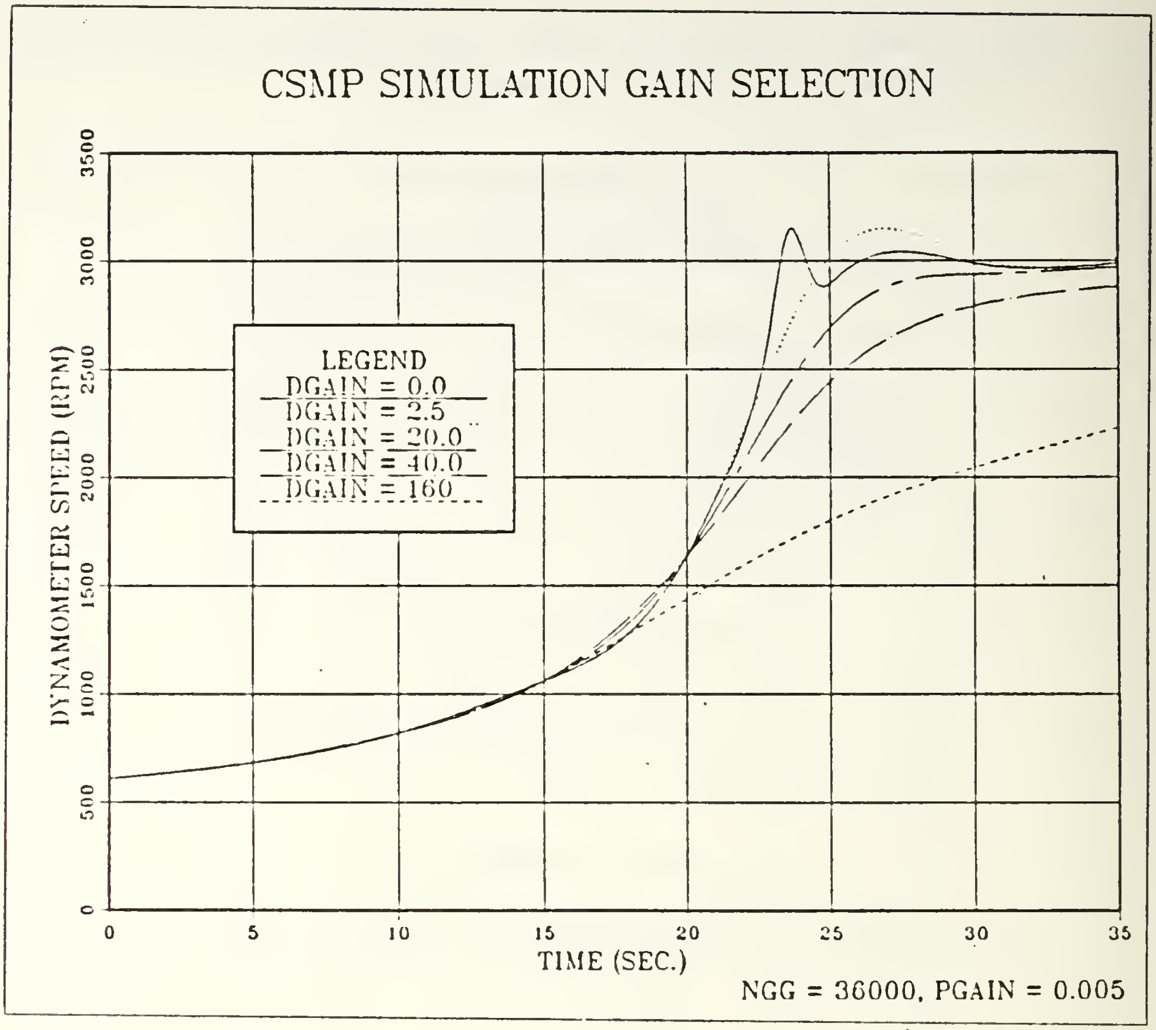

Figure 4.15 Derivative Gain Selection.

proportional gains produced oscillitions around the desired speed, whereas low gains failed to meet transient time requirements called for in the specifications. The selection of a gain of .005 was between these two limits and provided some margin for system and controller degradation.

The derivative gain was selected next, as shown in Figure 4.15 A derivative gain of 20.0 was selected to meet over shoot and transient requirements, again selecting a gain which best provided margins for safety.

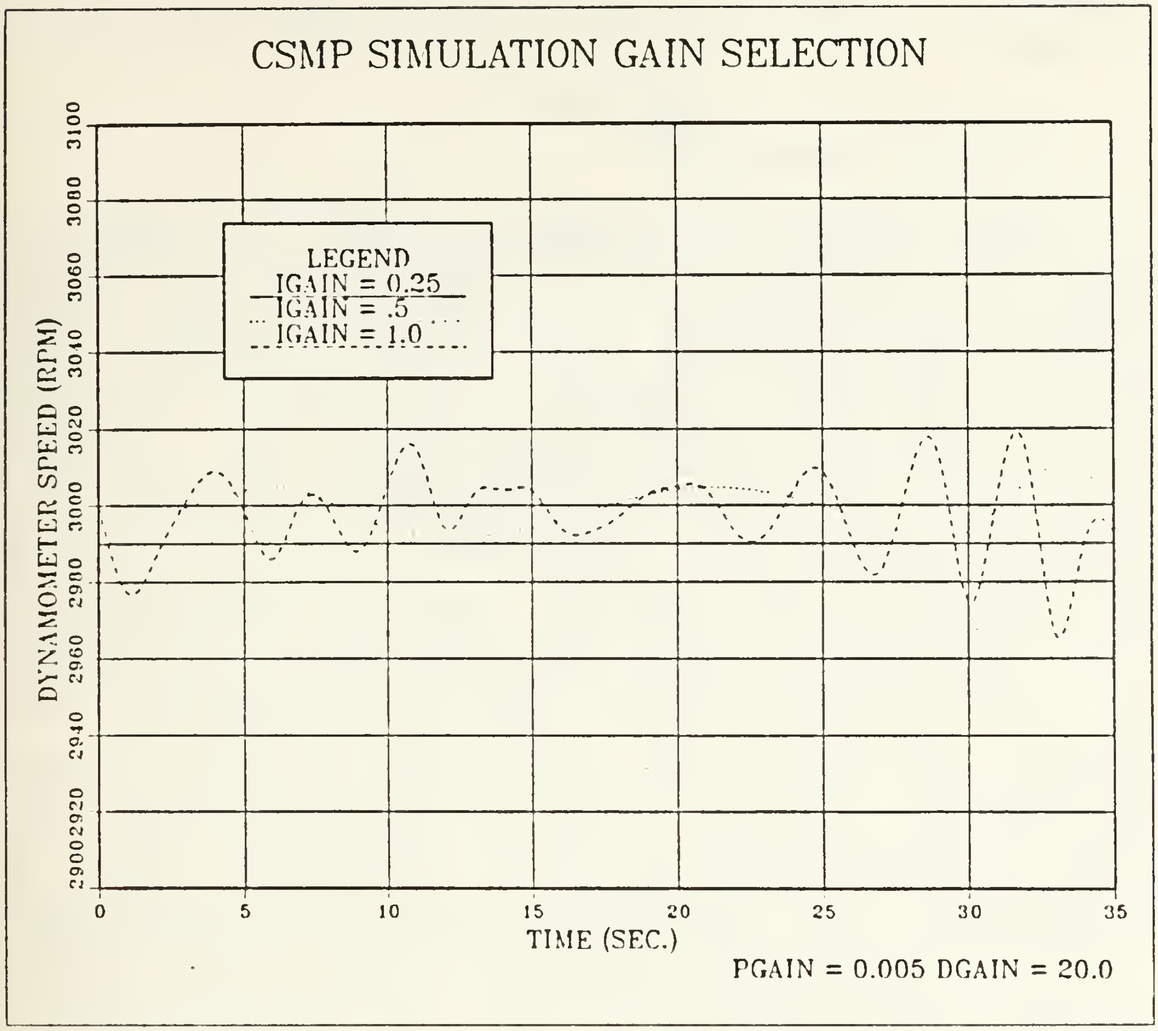

Figure 4.16 Integral Gain Selection.

Lastly, the integral gain was evaluated. An integral gain of .5 was initially selected to provide reset action in a ressonable period. In addition, the integrator output was limited to ± 100 to avoid saturation and balance the net controller output. Closer examination of the system behavior around set point showed that the integral action was generating a limit cycle when valve backlash occurred (Figure 4.16). However, the P-D controller provided a 1 percent error in speed regulation without the added

complexity of a PID controller, so the integral gain was set to zero.

F. CONTROLLER PROGRAMMING

Having selected proportional, integral, and derivative gains using CSMP III, efforts then centered on conversion of the control algorithm to a real time computer control program. The program was first written and tested in Tiny Basic. Cycle times of 400 miliseconds were experienced and it was decided that machine language was necessary to reduce cycle times to less than 100 milliseconds. Programming in machine language without the use of an assembler proved to be a formidable task. However, programing was facilitated by the development of macros for often-used control tasks. The program was structured so that control constants, such as gains and flags, were set in Basic to allow for easy modification. The control solution algorithm for real time control was performed in machine language for speed of execution. It is important to note that while gains were selected for a 100 millisecond cycle time, the inputs are sensed, control solution calculated, and output prepared in approximately 3 milliseconds. This provides ample time for later expansion into complex control algorithms. The overall improvement in performance between Basic and machine language speed of execution was observed to be approximately two orders of magnitude.

Both machine language and Basic suffer the same mathematical constraints of the 8073 microprocessor associated with sixteen bit fixed point arithmatic. This type of arithmatic requires a control program to continually check to determine if an overflow condition exists. Prechecks in addition and multiplication must be used to prevent the overflow condition from occurring.

V. CONCLUSIONS

Control development using a nonlinear simulation was successfull in the development of a marine propulsion emulator and speed regulator for a dynamometer. A control algorithm was developed using a CSMP III simulation which accurately depicted the performance of the system. The algorithm was translated directly to the microprocessor controller and successfully run as written. The good agreement between simulated and actual closed loop response thus validates the accuracy of both the control simulation and the approach to emulation. This also provides a plant model for future gas turbine controller development.

Machine language was required in order to realize real time solutions for the control algorithm. This was true even though system time constants were large and the algorithm was of modest size. It was determined that the equivalent control algorithm written in Tiny Basic ran 100 times slower than its machine language counter part.

Linearization of system performance for nonlinear systems can sometimes nullify the important characteristics which dominate the control problem. This was found in the area of valve dynamics modelling of the designed valves which transit at a constant rate. The limit cycle behavior predicted by a nonlinear model of valve dynamics would not have been observed with a linear valve model.

Numerous equations were developed to represent the steady state performance of both the dynamometer and power turbine. While they all represent the data to varying degrees, each had it's own complexity. Consequently, the selection of an appropriate equation was a tradeoff between knowledge of how the physical system should relate to inputs and what equation best fits the data.

Dynamometer pressures were assumed to be constant with the addition of the constant pressure regulator. The pressurization of the dynamometer was thought to improve the unload capacity and ease the modelling problem by providing a constant pressure drop across the valves. While pressurization helped to double the unload capacity, it did not fully correct for varying discharge pressures.

The use of slow synchronous stepper motors and an analog digital controller proved to be a successfull, low cost, simple, and effective means for controlling valve position. The valves were capable of regulating the flowrates from 0 to 200 lbm/min. It should be noted that while the motors provided good positioning of the 1 inch globe valves, they did contain some backlash. This effect was due to 3 degrees of resolution, which corresponded to approximately one half lbm/min near full closure.

VI. RECOMMENDATIONS

The data aquisition system could be improved by reprogramming it to take multiple readings in order to determine fluctuations in data and error. Currently, fuel flow data is entered manually. The installation of a turbine type flow meter could negate this requirement. The data acquistion system could also be interfaced with the turbine and dynamometer controllers to permit totally automatic data acquistion for a preprogrammed test schedule.

To reduce the burden of manually converting control algorithms into fast machine language code, an assembler should be obtained for the microprocessor.

The dynamometer unload valve performance was in poor agreement with the model. A detailed investigation of dynamometer discharge pressures and incorporation of this affect on the valve transfer function would substantially improve the simulations accuracy.

The current gas turbine control system was developed on short notice and has substantial room for improvement. A detailed study into the gas generator dynamics, as well as the development of an optimum controller, should be undertaken. Additional control loops which incorporate the turbine, dynamometer and gas generator could also be developed, thus providing a control system which is more in line with the bridge throttle lever concept where shaft speed is selected and the controller regulates to attain that speed. The emulation of sea state disturbances to be injected into proposed control systems could be performed in order to evaluate optimum designs. A start sequencer controller which provides automatic start up and operation of the turbine should be developed. This system could also monitor

vital parameters such as oil pressure, turbine inlet temperature, dynamometer and turbine speeds and take corrective action should they exceed normal operating limits.

APPENDIX A

CSMP SIMULATION PROGRAM

```
//JOHNSON JOB (2844,1431),'LAB2',CLASS=C
//*MAIN ORG=NPGVM1.2844P
//*FORMAT PR,DDNAME=PLOT.SYSVECTR,DEST=LOCAL
// EXEC CSMPXV
//X.PLOTPARM DD *
 &PLOT SCALE=.7 &END
//X.SYSIN DD *
*
*   PHILIP N JOHNSON
*
INITIAL
*   VALVE PARAMETERS
*   UNLOAD VALVE
     PARAM TU=0.0
     PARAM VPU=0.0
     CONSTANT KCU=1.54
*    LOAD VALVE
     PARAM TL=0.0
     PARAM VPL=0.0
     CONSTANT KCL=1.4366666
     CONSTANT MV=1.2
*    DYNAMIC PARAMETERS
     CONSTANT WINIT=1.85
     CONSTANT NDINIT=3000.0
     CONSTANT NDFIN=3000.0
     PARAM PGAIN=.00500
     CONSTANT TDGAIN=20.0
     CONSTANT TIGAIN=.25
*    CONSTANT TIGAIN=0.0
*    CONSTANT TDGAIN=0.0
     INCON NG=36000
*
DYNAMIC
*
     NOSORT
*    STEP SPEED DESIRED AT 5 SECONDS
*    FROM NDINIT TO NDFIN
     XXX = STEP (0.0)
     SSD=(NDFIN*XXX)+(ND*(1-XXX))
*
*    UNLOAD VALVE ACTUATOR
*
     UE=VLU-VPU
     EVU=DEADSP(-0.03,0.03,UE)
     UCV=FCNSW(EVU,0.0,0.0,MV)
     UOV=FCNSW(EVU,MV,0.0,0.0)
     TUDOT=UCV-UOV
     TU=INTGRL(0.0,TUDOT)
     VPU=KCU*TU
*    THIRD ORDER MASS FLOW RATE EQUATION
     UMDTT=(((1.163393487*(VPU)**3)-(10.94193298*(VPU)**2)...
         +(53.25267468*VPU)-7.88662148))/60
     UMDOT=LIMIT(0.0,200.0,UMDTT)
*    FIRST ORDER MASS FLOW RATE EQUATION
*    UMDOT=35.07 * VPU/60
*
*    LOAD VALVE ACTUATOR
*
     LE=VLL-VPL
```

```
      EVL=DEADSP(-0.03,0.03,LE)
      LCV=FCNSW(EVL,0.0,0.0,MV)
      LOV=FCNSW(EVL,MV,0.0,0.0)
      TLDOT=LCV-LOV
      TL=INTGRL(0.0,TLDOT)
      VPL=KCL*TL
*     THIRD ORDER MASS FLOW RATE EQUATION
      LMDTT=(((4.67291038*(VPL)**3)-(41.60427991*(VPL)**2)...
            +(146.27120228*VPL)-12.07589))/60
      LMDOT=LIMIT(0.0,200.0,LMDTT)
*     FIRST ORDER MASS FLOW RATE EQUATION
*     LMDOT= 100*VPL/60
*
*     INTEG DYNO WATER VOLUME
*
      W2=LMDOT-UMDOT
      W1=INTGRL(WINIT,W2)
      W=LIMIT(0.0,48.0,W1)
*
*     CALC DYNAMICS
*
*     INERTIA * CONSTANT
      F1=(.6738)*(.10471976)
*     POWER TURBINE TORQUE
      F2=(-725.76+(0.0363642*(NG)))+(0.05267138...
          -(4.454586E-6*(NG)))*(ND)
*     DYNAMOMETER TORQUE
*     FIRST ORDER EQUATION
*     F3=((.112659205+3.1511985E-2*(W))*(ND))-205
*     SECOND ORDER EQUATION
      F3=-20+((0.00046*(W/16.6)**1.3)+4.00E-6)*(ND**2)
      NDDOT=(1/F1)*(F2-F3)
      ND=INTGRL(NDINIT,NDDOT)
      BHP = ND*F3*(2.0*3.1415/33000.)
*
*     CONTROL SECTION
*
*     ANALOG TO DIGITAL CONVERSION 100 MILLISECOND CYCLE TIME
*
      SST=IMPULS(0.0,0.1)
      SAM=ZHOLD(SST,ND)
      IF(SST.EQ.0.0) GO TO 1
*     ONLY PERFORM CONTROL AT CYCLE INTERVAL
*     ERR CAN BE FROM 0 TO 3000
      ERR=SSD-SAM
      DNSERR = DERIV(0.0,ERR)
*     INSERR = INTGRL(0.0,ERR)
      INSERR = INSERR +(ERR/10)
      DNDERR = DNSERR/10.0
*     INDERR = INSERR/10.0
      INDERR = LIMIT(-100.0,100.0,INSERR)
      INSERR = INDERR
      V1=PGAIN*ERR
      V2=PGAIN*(TIGAIN*INDERR)
      V3A=PGAIN*(TDGAIN*DNDERR)
      V3 = LIMIT(-10.0,10.0,V3A)
*     V3 LIMITED FOR DISPLAY ONLY NO EFFECT ON CONTROL
      V=V1+V2+V3
      VELX=LIMIT(-3.5,0.0,V)
      VEL=-VELX
      VEU=LIMIT(0.0,4.0,V)
    1 CONTINUE
*     VALVE VOLTAGE LIMITS
*     DIGITAL TO ANALOG CONVERSION
      VLL = ZHOLD (SST,VEL)
      VLU = ZHOLD (SST,VEU)
      SORT
      END OF LOOP
      TIMER FINTIM = 40.0, OUTDEL = 0.20, PRDEL = 0.20
```

```
TERMINAL
*     PRINTER PLOT
*     PRTPLT V,V1,V2,V3
*     LABEL TIME VS. OUTPUT P I D
*     PRTPLT ERR,INDERR,DNDERR
*     LABEL TIME VS. CALC PID
*     PRTPLT VLL,VPL,LMDOT,W
*     LABEL TIME VS. LOADVALVE
*     PRTPLT VLU,VPU,UMDOT,W
*     LABEL TIME VS. UNLOADVALVE
      PRTPLT W,ND,BHP
      LABEL TIME VS WATER SPEED POWER
*     PRTPLT NG,ND,NDDOT,W,F1,F2,F3
*     LABEL TIME VS. SIGNALS
*     VERSITEC PLOT
*     OUTPUT TIME , ND
*     PAGE XYPLOT
*     LABEL TIME VS. DYNO SPEED
*     OUTPUT TIME , W
*     PAGE XYPLOT
*     LABEL TIME VS. WATER WT.
*     OUTPUT TIME , V,V1,V2,V3
*     PAGE XYPLOT
*     LABEL TIME VS. ERRORS
END
STOP
ENDJOB
/*
```

APPENDIX B

BASIC CONTROL PROGRAM

VARIBLES USED:

A	ACTUAL TURBINE SPEED
B	DESIRED TURBINE SPEED
C	TURBINE CONTROL GAIN
D	DYNO DERIVATIVE CONTROL GAIN
E	DYNO SPEED ERROR (N-M)
F	DYNO DERIVATIVE SIGNAL
G	DYNO INTEGRAL SIGNAL
H	MARINE SIMULATION FLAG (1=ON,0=OFF)
I	DYNO INTEGRAL GAIN
J	DYNO INTEGRAL
K	DYNO MAXIMUM INTEGRAL LIMIT +/-
L	TEMP STORAGE
M	DYNO ACTUAL SPEED
N	DYNO DESIRED SPEED
O	DYNO LAST CYCLE SPEED FOR DERIVATIVE
P	DYNO PROPORTIONAL GAIN
Q	TEMP STORAGE
R	DYNO MAXIMUM DERIVATIVE LIMIT
S	DYNO MINIMUM EFFECTIVE DERIVATIVE LIMIT
T	NOT USED
U	DYNO FLOW SIGNAL INVERSE (-V)
V	DYNO FLOW VALVE SIGNAL
W	TURBINE THROTTLE OUTPUT
X	DYNO VARIBLE GAIN CONTROLLER FLAG (1=ON,0=OFF)
Y	TURBINE TEMP STORAGE
Z	TURBINE INTEGRATED THROTTLE VALUE

BASIC CONTROL PROGRAM

```
10 P=2
20 I=0
30 D=20:R=4000:S=4
40 K=100
50 C=100:X=0
60 PRINT ENTER TURBINE SPEED / 10 (1700-3650) ,
70 INPUT B
80 IF B<1700 THEN PRINT TO LOW:GOTO 60
90 IF B>3650 THEN PRINT TO HIGH:GOTO 60
100 MARINE PROPULSION SIMULATION ? (YES=1,NO=0)
110 INPUT H
120 IF H=1 THEN GOTO 170
130 PRINT ENTER DYNAMOMETER SPEED (500-3000),
140 INPUT N
150 IF N<500 THEN PRINT TO LOW:GOTO 130
160 IF N>3000 THEN PRINT TO HIGH:GOTO 130
```

```
170 PRINT
180 PRINT CONTROL SETPOINTS
190 PRINT TURBINE SPEED = ,N
200 PRINT DYNAMOMETER SPEED = ,B
210 B=B*2-3228
220 LINK #1400
230 GOTO 60
```

APPENDIX C

8073 ASSEMBLY LANGUAGE PROGRAM

ADD	INSTRUCTION	LABEL	MNEMONIC	COMMENT
1450	C4 08	TRIG A	LDA 08	07+01 =CHANNEL 1
1452	27 10 0A		LD P3,0A10	ADC CHANNEL ADDRESS
1455	CB 00		ST A,P3+00	
1457	C4 FF	DELAY A	LD A,FF	CYCLE 256 TIMES
1459	00		NOP	
145A	00		NOP	
145B	00		NOP	
145C	00		NOP	
145D	00		NOP	
145E	00		NOP	
145F	00		NOP	
1460	FC 01		SUB A,01	SUBTRACT 1 FORM A
1462	00		NOP	
1463	00		NOP	
1464	00		NOP	
1465	00		NOP	
1466	00		NOP	
1467	00		NOP	
1468	00		NOP	
1469	7C EE		BNZ #EE	IF A<>0 GO BACK 17 STEPS
146B	00		NOP	
146C	00		NOP	
146D	00		NOP	
146E	00		NOP	
146F	27 00 10	READ A	LD P3#1000	BASIC ADDRESS TABLE
1472	26 10 0A		LD P2,0A10	ADC READ ADDRESS
1475	82 01		LD EA,P2+01	LOAD EA P2,0A11,2
1477	01		XCH E WITH A	CONDITION INPUT
1478	0C		SR EA	
1479	0C		SR EA	
147A	0C		SR EA	
147B	0C		SR EA	
147C	8B 18		ST EA,P3+18	STORE1018,9 'M'
147E	00		NOP	
147F	00		NOP	
1480	C4 09	TRIG B	LD A 09	07+02 =CHANNEL 2
1482	27 10 0A		LD P3 0A10	ADC CHANNEL ADDRESS
1485	CB 00		ST A,P3+00	
1487	C4 FF	DELAY B	LD AFF	CYCLE 256 TIMES
1489	00		NOP	

```
148A 00                     NOP
148B 00                     NOP
148C 00                     NOP
148D 00                     NOP
148E 00                     NOP
148F 00                     NOP
1490 FC 01                  SUB A,#01          SUBTRACT 1 FORM A
1492 00                     NOP
1493 00                     NOP
1494 00                     NOP
1495 00                     NOP
1496 00                     NOP
1497 00                     NOP
1498 00                     NOP
1499 7C EE                  BNZ 20             IF A<>0 GO BACK 17 STEPS
149B 00                     NOP
149C 00                     NOP
149D 00                     NOP
149E 00                     NOP
149F 27 00 10      READ B   LD P3 1000         BASIC ADDRESS TABLE
14A2 26 10 0A               LD P2 0A10         ADC READ ADDRESS
14A5 82 01                  LD EA,P2+01        LOAD EA P0A11,2
14A7 01                     XCH E WITH A       CONDITION INPUT
14A8 0C                     SR EA
14A9 0C                     SR EA
14AA 0C                     SR EA
14AB 0C                     SR EA
14AC 8B 00                  ST EA,P3+00        STORE 1000,1A
14AE 00                     NOP
14AF 00                     NOP
14B0 84 00 00      IF H=1   LD EA0000          IF H=1 SIMULATE DYNO SPEED
14B3 BB 0E                  ADD EA P3+0E       ADD H
14B5 6C 0D                  BZ 0D              BRANCH IF ZERO +12
14B7 B4 6C 07               LD EA076C          LOAD EA WITH 1900 DEC
14BA B3 00                  ADD EA,P3+00       ADD EA WITH 1000,1 A
14BC A4 02 00               LD T 0002
14BF 0D                     DIV
14C0 8B 1A                  ST EA,P3+1A        STORE EA 1001A,B N
14C2 00                     NOP
14C3 00                     NOP
14C4 84 00 00      IF X=1   LD EA#0000         IF X=1 TURN ON VARIBLE GAIN
14C7 BB 2E                  ADDEA P3+2E        ADD X
14C9 6C 10                  BZ 10              BRANCH IF ZERO + 16
14CB 83 18                  LD EA,P3+00        LOAD EA WIT1000 A
14CD A4 90 02               LD T,#0290         LOAD T WITH 2000 DEC
14D0 0D                     DIV
14D1 8B 20                  ST EA,P3+20        STORE 1020,1 Q TEMP
14D3 84 05 00               LD EA0005
```

```
14D6 BB 20                   SUB EA,P3+20    SUBTRACT1020,1 Q
14D8 8B 1E                   ST EA,P3+1E     STORE 101E,F P
14DA 00                      NOP
14DB 83 02        IFB-A>C    LD EA,P3+02     LOAD EA 1002,3 B
14DD BB 00                   SUB EA,P3+00    SUBTRACT 1000,1 A
14DF 8B 30                   ST EA,P3+30     STORE EA 1030,1 Y
14E1 83 04                   LD EA,P3+04     LOAD EA  1004,5 C
14E3 09                      LD T WITH EA
14E4 BB 30                   SUB EA,P3+30    SUBTRACT 1030,1 Y
14E6 01                      XCH A WITH E    LOOK AT HIGH BYTE FOR SIGN
14E7 64 03                   BP 03           BRANCH IF POSITIVE +3
14E9 0B                      LD EA WITH T
14EA 8B 30                   ST EA,P3+30     STORE EA 1030,1 Y
14EC 00                      NOP
14ED 83 30     IFB-A<-C      LD EA,P3+30     LOAD EA 1030,1 Y
14EF B3 04                   ADD EA,P3+04    ADD EA 1004,5  C
14F1 01                      XCH A WITH E    LOOK AT HIGH BYTE FOR SIGN
14F2 64 07                   BP 07           BRANCH IF POSITIVE
14F4 84 00 00                LD EA  0000
14F7 BB 04                   SUB EA,P3+04    SUBTRACT 1004,5 C
14F9 8B 30                   ST EA,P3+30     STORE EA 1030,1 Y
14FB 83 32        Z+Y        LOAD EA,P3+32   LOAD EA 1032,3 Z
14FD B3 30                   ADD EA,P3+30    ADD EA  1030,1 Y
14FF 8B 32                   ST EA,P3+32     STORE EA 1032,3 Z
1501 84 FF 4F IFZ>20480      LD EA# 4FFF     LOAD EA WITH 4095 DEC
1504 09                      LD T WITH EA
1505 BB 32                   SUB EA,P3+32    SUBTRACT 1032,3 Z
1507 01                      XCH A WITH E    LOOK AT HIGH BYTE FOR SIGN
1508 64 03                   BP 03           BRANCH IF POSITIVE +03
150A 0B                      LD EA WITH T
150B 8B 32                   ST EA,P3+32     STORE EA1032,3 Z
150D 84 00 00 IF Z<0         LD EA 0000      LOAD EA WITH 0
1510 09                      LD T WITH EA
1511 83 32                   LD EA,P3+32     LOAD 1032,3 Z
1513 01                      XCH A WITH E
1514 64 03                   BP 03           BRANCH IF POSITIVE +3
1516 0B                      LD EA WITH T
1517 8B 32                   ST EA,P3+32     STORE 0 1032,3 Z
1519 83 32        W=Z/5      LD EA,P3+32     LOAD EA 1032,3 Z
151B A4 05 00                LD T 0005       LOADT WITH 5
151E 0D                      DIV
151F 8B 2C                   ST EA,P3+2C     STORE EA 102C,D W
1538 0B                      LD EA WITH T
1539 8A 12                   ST EA,P2+ 12    STORE1012,3 J
153B 00                      NOP
153C 82 12       J<-K,J=-K   LD EA,P2+ 12    LOAD 1012,3 J
153E B2 14                   ADD EA,P2+ 14   ADD 1014,5 K
1540 01                      XCH A WITH E    LOOK AT HIGH BYTE FOR SIGN
```

```
1541 64 07                      BP 07             BRANCH IF POSITIVE +07
1543 84 00 00                   LD EA 0000
1546 BA 14                      SUB EA,P2+ 14     SUBTRACT 1014,5 K
1548 8A 12                      ST EA,P2+ 12      STORE 1012,3 J
154A 00                         NOP
1549 00                         NOP
154A 00                         NOP
154B 00                         NOP
154C 00                         NOP
154D 00                         NOP
154E 00                         NOP
154F 00                         NOP
1550 26 00 10   IF(E-0)>HI      LD PZ=1000        PZ=BASIC VARIABLE ADDS TBL
1553 A2 06                      LD T,PZ+06        LOAD T 1006,7 D
1555 84 FF 7F                   LD EA 7FFF        7FFF=+32767
1558 0D                         DIV               EA WITH EA/T
1559 8A 16                      ST EA,PZ+16       STORE EA 1016,17 L
155B 09                         LD T WITH EA
155C 82 08                      LD EA,PZ+08       LOAD EA 1008,9 E
155E BA 1C                      SUB EA, PZ+1C     SUBTRACT EA WITH 101C 0
1550 8A 20                      ST EA, PZ+20      STORE EA 1020,27Q"
1562 0B                         LD EA WITH T
1563 BA 20                      SUB EA, PZ+20     SUBTRACT EA WITH 1020 Q
1565 01                         XCH A WITH E      LOOK AT HI BYTE FOR SIGN
1566 64 03                      BP 03             BRANCH IF POSITIVE AHEAD 03
1568 0B                         EA WITH T
1569 8A 20                      ST EA, PZ+20      STORE EA 1020,21 Q
156B 00                         NOP
156C 00         F(E-0)<LOW      NOP
156D 00                         NOP
156E 82 20                      LD EA PZ+20       LOAD EA 1020,21 Q
1570 B2 16                      ADD EA,PZ+16      ADD EA WITH 1016,17 L
1572 01                         XCH E WITH A      LOOK AT HIGH BYTE
1573 64 07                      BP 07             BRANCH IF POSITIVE + 07
1575 84 00 00                   LD EA 0000        LOAD EA WITH 0
1578 BA 16                      SUB EA,P2+16      SUBTRACT  1016,17 L
157A 8A 20                      ST EA, PZ+20      STORE EA, 1020,21 Q
157C 00                         NOP
157D 00                         NOP               MULTIPLY DERIVITIVE GAIN
157E A2 20      F=D*(E-0)       LD T, PZ +20      LOAD T    1020,21 Q
1580 82 06                      LD EA, PZ+06      LOAD EA   1006,7 D
1582 2C                         MULT              EA  T= EA*T (LOW BYTE IN T)
1583 0B                         LD EA WITH T      GET LOWER 16 BIT'S
1584 8A 0A                      ST EA, PZ+0A      STORE EA  100A,B F
1586 00                         NOP
1587 00                         NOP
1588 00                         NOP
1589 00                         NOP
```

```
154A 82 08      Q=E-0        LD EA, PZ+08     LOAD EA  1008,9 E
154C BA 1C                   SUB EA, PZ+1C    SUBTRACT EA 101C,D 0
154E 8A 20                   ST EA, PZ +20    STORE EA 1020,1 Q
1550 A4 01 00   Q>S T=1      LD T 0001
1553 82 24                   LD EA, PZ+24     LOAD EA  1024,5 S
1555 BA 20                   SUB EA, PZ +20   SUBTRACT EA  1020 Q
1557 01                      XCH              CHECK HI BYTE FOR SIGN
1558 64 03                   BP + 03          BRANCH IF POSITIVE
155A 0B                      LD EA WITH T     LOAD EA WITH 1
155B 8A 26                   ST EA, PZ+26     STORE EA  1024,5 S
1561 01                      XCH              CHECK HI BYTE FOR SIGN
1562 64 03                   BP
1564 08                      LD EA WITH T
1565 8A 26                   ST EA, PZ+26     STORE EA  1026,7 T
1567 82 26                   LD EA, PZ+26     LOAD EA   1026,7 T
1569 7C 05                   BNZ +  05
156B 84 00 00                LD EA 0000
156E 8A 20                   ST EA, PZ+20     STORE EA  1020,1 Q
1570 A2 06        L=7FFF/D   LDT, PZ+06       LOAD T  1006,7 D
1572 84 FF 7F                LD EA 7FFF       +32767
1575 0D                      DIV              EA=EA/T
1576 8A 16                   ST EA, PZ+16     STORE EA  1016,7 L
1578 09           IF Q>L W   LD T WITH EA     LOAD T WITH EA
1579 84 00 00                LD EA D
157C 8A 26                   ST EA PZ+26      STORE T
158A 00                      NOP
158B 00                      NOP
158C 00                      NOP
158D 00                      NOP
158E 00                      NOP
158F 00                      NOP
1590 82 22      F>R F=R      LD EA, PZ+22     LOAD 1022,3 R
1592 09                      LD T WITH EA
1593 BA 0A                   SUB EA, P2+0A
1595 01                      XCH A WITH E     LOOK AT HI BYTE FOR SIGN
1596 64 03                   BP 03            BRANCH IF POSITIVE +3
1598 0B                      LD EA WITH T
1599 BA 0A                   ST EA P2 + 0A    STORE 100A,B F
159B 00                      NOP
159C 82 0A     F<-R F=-R     LD EA P2 +0A
159E B2 22                   ADD EA, P2+22    ADD EA WITH 1022,3 R
15A0 01                      XCH A WITH E     LOOK AT HIGH BYTE FOR SIGN
15A1 64 07                   BP 07            BRANCH IF POSITIVE +07
15A3 84 00 00                LD EA 0000
15A6 BA 22                   SUB EA,P2+22     SUBTRACT 10022,3 R
15A8 8A 0A                   ST EA,P2 + 0A    STORE EA  100A,B F
15AA 00                      NOP
15AB 00                      NOP
```

```
15AC 00                          NOP
15AD 00                          NOP
15AE 00                          NOP
15AF 00                          NOP
15B0 A2 12    G=J*I              LD T,P2 + 12     LOAD T   1012,3 J
15B2 82 10                       LD EA,P2 + 10    LOAD EA  1010,11 I
15B4 2C                          MULT
15B5 0B                          LD EA WITH T     USE LOWER 16 BITS
15B6 8A 0C                       ST EA,P2+0C      STORE EA  100C,D G
15B8 82 08         O=E           LD EA,P2+08      LOAD EA 1008,9 E
15BA 8A 1C                       ST EA,P2+1C      STORE EA 101C,D O
15BC A2 1E                       LD T ,P2+1E      LOAD T  101E,F P
15BE 84 FF 7F                    LD EA 7FFF       LOAD EA +32767
15C1 0D                          DIV              EA WITH EA/T
15C2 8A 16                       ST EA, PZ+16     STORE EA 1016,7 L
15C4 09                          LD T WITH EA
15C5 82 08                       LD EA,PZ+08      LOAD EA WITH  1008,9 E
15C7 B2 0A                       ADD EA, PZ+OA    ADD EA WITH   100A,B F
15C9 B2 0C                       ADD EA, PZ+OC    ADD EA WITH   100C,D G
15CB 8A 20                       ST EA,PZ+20      STORE EA WITH  1020 Q
15CD 0B                          LD EA WITH T
15CE BA 20                       SUB EA,PZ+20     SUBTRACT EA  1020 Q
15D0 01                          XCH AWITH E      LOOK AT HI BYTE FOR SIGN
15D1 64 03                       BP 03            BRANCH IF POSITIVE 03
15D3 0B                          EA WITH T
15D4 8A 20                       ST EA, PZ+20     STORE EA 1020,21 Q
15D6 00                          NOP
15D7 00                          NOP
15D8 00       IF E+F+G<100       NOP
15D9 82 20                       LD EA, PZ;20     LOAD EA  1020,21 Q
15DB B2 16                       ADD EA, PZ+16    ADD EA WITH 1016,7 L
15DD 01                          XCH E WITH A     LOOK AT HIGH BYTE FOR SIGN
15DE 64 07                       BP 07            BRANCH IF POSITIVE + 07
15E0 84 00 00                    LD EA 0000
15E3 BA 16                       SUB EA, PZ+16    SUBTRACT EA 1016,17 L
15E5 8A 20                       ST EA, PZ+20     STORE EA 1020,1 Q
15E7 00
15E8 00
15E9 A2 20 (E+F+G)   LD T,       PZ+20      LOAD T1020,1 Q
15EB 82 1E                       LD EA, PZ+1E     LOAD EA 101E,F P
15ED 2C                          MULT             EA  T=EA*T
15EE 0B                          LD EA WITH T     GET-LOWER 16 BITS
15EF 8A 2A                       ST EA PZ+2A      STORE EA 102A,B V
15F1 00                          NOP
15F2 00                          NOP
15F3 00                          NOP
15F4 00                          NOP
15F5 00                          NOP
```

```
15F6 00                        NOP
15F7 00                        NOP
15F8 00                        NOP
15F9 00                        NOP
15FA 00                        NOP
15FB 00                        NOP
15FC 00                        NOP
15FD 00                        NOP
15FE 00                        NOP
15FF 00                        NOP
1600 26 00 10 IF V>3200        LD PZ 1000         BASIC ADDRESS TABLE
1603 84 80 0C                  LD EA 0080         3200 DEC   4 VOLTS
1606 8A 16                     ST EA,PZ+16        STORE EA  1016,7 L
1608 09                        LD T WITH EA
1609 BA 2A                     SUB EA PZ+2A       SUBTRACT EA 102A,B V
160B 01                        XCH E WITH A       CHECK HI BYTE FOR SIGN
160C 64 03                     BP + 03            BRANCH IF POSITIVE +3
160E 0B                        LD EA WITH T
160F 8A 2A                     ST EA, PZ+2A       STORE EA 102A,B V
1611 84 CB 0A IF V<-2760       LD EA 0ACB         2760 DEC   3.5 VOLTS
1614 8A 16                     ST EA,PZ+16        STORE EA1016,17 L
1616 82 2A                     LD EA,PZ+2A        LOAD EA 102A,B V
1618 B2 16                     ADD EA,PZ+16       ADD EA  1016,7 L
161A 01                        XCH E WITH A       CHECK HIGH BITE FOR SIGN
161B 64 07                     BP 07              BRANCH IF POSITIVE + 07
161D 84 00 00                  LD EA 0000
1620 BA 16                     SUB EA,PZ+16       SUBTRACT EA 1016,7 L
1622 8A 2A                     ST EA,PZ +2A       STORE EA 102A,B V
1624 00                        NOP
1625 00                        NOP
1626 00                        NOP
1627 00                        NOP
1628 00                        NOP
1629 00                        NOP
162A 00                        NOP
162B 00                        NOP
162C 00                        NOP
162D 00                        NOP
162E 00                        NOP
162F 00                        NOP
1630 84 00 00    U=-V          LD EA WITH 0000
1633 BA 2A                     SUB EA,P2 +2A      SUBTRACT EA 102A,V
1635 8A 28                     ST EA,P2+28        STORE EA 1028,9 U
1637 00                        NOP
1638 27 00 F0    IFV>=0        LD P3 F000         DAC ADDRESS
163B 82 2A                     LD EA,P2+2A        LOAD EA 102A,B V
163D 01                        XCH                CHECK SIGN
163E 64 02                     BP+ 02             BRANCH IF POSITIVE 02
```

```
1640 74 0F                  BRA               BRANCH UNCONDITIONALY + 0F
1642 84 00 00               LD EA 0000        LOAD EA WITH 0
1645 8B 02                  ST EA,P3+02       STORE EA F002,3 CLOSE
1647 82 2A                  LD EA,P2+2A       LOAD EA WITH P102A V
1649 0C                     SR EA             ADJUST VARIBLE FOR OUTPUT
164A 0C                     SR EA
164B 0C                     SR EA
164C 0C                     SR EA
164D 8B 00                  ST EA,P3+00       STORE EA F0000,1
164F 74 13                  BRA               BRANCH UNCONDITIONALY +13
1651 84 00 00   V<0         LD EA 0000
1654 8B 00                  ST EA,P3+00       STORE EA  000,1 CLOSE
1656 82 28                  LD EA,P2+28       LOAD E 1028,9 U
1658 0C                     SR EA             ADJUST VARIBLE FOR DAC
1659 0C                     SR EA
165A 0C                     SR EA
165B 0C                     SR EA
165C 8B 02                  ST EA, P3+02      STORE EA F002,3
165E 00                     NOP
165F 00                     NOP
1660 00                     NOP
1661 00                     NOP
1662 00                     NOP
1694 82 2C  THROTTLE        LD EA,P2+2C       LOAD EA 102C,D W
1696 0C                     SR EA             CONDITION OUTPUT
1697 0C                     SR EA
1698 0C                     SR EA
1699 0C                     SR EA
169A 8B 04                  ST EA,P3+04       STORE AT DAC C
169C 00                     NOP
169D 00                     NOP
169E 00                     NOP
169F 00                     NOP
16A0 8B 06  TRIG DAC        ST EA,P3+06       OUTPUT DAC VOLTAGES
16A2 27 00 0A BUTTON        LD P3 0A00
16A5 C3 01                  LD A,P3+00
16A7 D4 80                  AND A WITH 80      CHECK HIGH BIT
16A9 7C 11                  BNZ 11            BRANCH IF NOT ZERO
16AB 26 00 F0               LD P2 F000
16AE 84 00 00               LD EA 0
16B1 8A 00                  ST EA P2+00       CLOSE VALVE
16B3 8A 02                  ST EA,P2+02       CLOSE VALVE
16B5 8A 06                  ST EA,P2+06       EXICUTE
16B7 5C                     RTN               RETURN TO BASIC
16B8 00                     NOP
16B9 00                     NOP
16BA 27 00 00   CLOCK       LD P3 0A00
16BD C4 FF                  LD A FF           TURN ON LED
```

```
16BF CB 00             ST A,P3+00
16C1 C3 00             LD A,P3+00       READ CLOCK
16C3 D4 80             AND A WITH 80    CHECK HIGH BIT
16C5 7C FA             BNZ FA           BRANCH IF NOT ZERO -5
16C7 CB 00             ST A,P3+00       TURN OFF LED
16C9 30                LD EA WITH PC
16CD BC CA 02          SUB EA 02CA      RELATIVE PROGRAM START
16D0 4C                XCH PC WITH EA
```

MEMORY DUMP

```
1100  31 30 20 50 3D 32 0D 32 30 20 49 3D 30 0D 33 30   10 P=2.20 I=0.30
1110  20 44 3D 32 30 3A 52 3D 34 30 30 30 3A 53 3D 34    D=20:R=4000:S=4
1120  0D 34 30 20 4B 3D 35 30 0D 35 30 20 58 3D 30 0D   .40 K=50.50 X=0.
1130  36 30 20 43 3D 31 30 30 0D 37 30 20 50 52 20 22   60 C=100.70 PR
1140  20 22 0D 38 30 20 50 52 20 22 45 4E 54 45 52 20     .80 PR ENTER
1150  54 55 52 42 49 4E 45 20 53 50 45 45 44 20 2F 20   TURBINE SPEED /
1160  31 30 20 28 31 37 30 30 2D 33 36 35 30 29 22 3B   10 (1700-3650);
1170  0D 39 30 20 49 4E 50 55 54 20 42 0D 31 30 30 20   .90 INPUT B.100
1180  49 46 20 42 3C 31 37 30 30 54 48 45 4E 50 52 22   IF B<1700THENPR
1190  54 4F 20 4C 4F 57 22 3A 47 4F 31 30 0D 31 31 30   TO LOW:GO10.110
11A0  20 49 46 20 42 3E 33 36 35 30 54 48 45 4E 50 52    IF B>3650THENPR
11B0  22 54 4F 20 48 49 47 48 22 3A 47 4F 31 30 0D 31   TO HIGH:GO10.1
11C0  32 30 20 50 52 22 20 22 0D 31 33 30 20 50 52 22   20 PR .130 PR
11D0  50 52 4F 50 55 4C 53 49 4F 4E 20 45 4D 55 4C 41   PROPULSION EMULA
11E0  54 49 4F 4E 20 3F 20 28 31 3D 59 45 53 2C 30 3D   TION ? (1=YES,0=
11F0  4E 4F 29 22 3B 0D 31 34 30 20 49 4E 50 55 54 20   NO);.140 INPUT
1200  48 0D 31 35 30 20 49 46 20 48 3D 31 20 54 48 45   H.150 IF H=1 THE
1210  4E 20 47 4F 32 31 30 0D 31 36 30 20 50 52 22 20   N GO210.160 PR
1220  22 0D 31 37 30 20 50 52 20 22 45 4E 54 45 52 20   .170 PR ENTER
1230  44 59 4E 41 4D 4F 4D 45 54 45 52 20 53 50 45 45   DYNAMOMETER SPEE
1240  44 20 28 35 30 30 2D 33 30 30 30 29 22 3B 0D 31   D (500-3000);.1
1250  38 30 20 49 4E 50 55 54 20 4E 0D 31 39 30 20 49   80 INPUT N.190 I
1260  46 20 4E 3C 35 30 30 20 54 48 45 4E 20 50 52 20   F N<500 THEN PR
1270  22 54 4F 20 4C 4F 57 22 3A 47 4F 20 31 36 30 0D   TO LOW:GO 160.
1280  32 30 30 20 49 46 20 4E 3E 33 30 30 30 20 54 48   200 IF N>3000 TH
1290  45 4E 20 50 52 20 22 54 4F 20 48 49 47 48 22 3A   EN PR TO HIGH:
12A0  47 4F 20 31 36 30 0D 32 31 30 20 50 52 20 22 20   GO 160.210 PR
12B0  22 0D 32 32 30 20 50 52 20 22 43 4F 4E 54 52 4F   .220 PR CONTRO
12C0  4C 20 53 45 54 50 4F 49 4E 54 53 22 0D 32 33 30   L SETPOINTS.230
12D0  20 50 52 20 22 20 22 0D 32 34 30 20 50 52 20 22    PR  .240 PR
12E0  54 55 52 42 49 4E 45 20 3D 20 22 2C 42 2C 22 20   TURBINE = ,B,
12F0  78 20 31 30 22 0D 32 35 30 20 50 52 20 22 20 22   X 10.250 PR
1300  0D 32 36 30 20 50 52 20 22 44 59 4E 41 4D 4F 4D   .260 PR DYNAMOM
1310  45 54 45 52 20 3D 20 22 2C 4E 0D 32 36 35 20 42   ETER = ,N.265 B
1320  3D 42 2A 32 2D 33 32 32 38 0D 32 37 30 20 4C 49   =B*2-3228.270 LI
```

```
1330  4E 4B 23 31 34 30 30 0D 32 38 30 20 47 4F 20 31   NK#1400.280 GO 1
1340  30 0D 32 39 30 20 53 54 4F 50 0D 7F 7F 0D 7F 4C   0.290 STOP..L
1350  49 4E 4B 23 31 35 30 30 0D 32 38 30 20 47 4F 20   INK#1500.280 GO
1360  37 30 0D 32 39 30 20 53 54 4F 50 0D 7F 0D 32 37   70.290 STOP..27
1370  30 20 4C 49 4E 4B 23 31 35 30 30 0D 32 38 30 20   0 LINK#1500.280
1380  47 4F 20 37 30 0D 32 39 30 20 53 54 4F 50 0D 7F   GO 70.290 STOP.
1390  32 37 30 20 4C 49 4E 4B 23 31 35 30 30 0D 32 38   270 LINK#1500.28
13A0  30 20 47 4F 20 37 30 0D 32 39 30 20 53 54 4F 50   0 GO 70.290 STOP
13B0  0D 7F 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
13C0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
13D0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
13E0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
13F0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
1400  C4 08 27 10 0A CB 00 C4 FF 00 00 00 00 00 00 00   ..'.............
1410  FC 01 00 00 00 00 00 00 00 7C EE 00 00 00 00 27   .........|.....'
1420  00 10 26 10 0A 82 01 01 0C 0C 0C 0C 8B 18 00 00   ................
1430  C4 09 27 10 0A CB 00 C4 FF 00 00 00 00 00 00 00   ..+.............
1440  FC 01 00 00 00 00 00 00 00 7C EE 00 00 00 00 27   .........|.....'
1450  00 10 26 10 0A 82 01 01 0C 0C 0C 0C 8B 00 00 00   ................
1460  84 00 00 BB 0E 6C 0D 84 6C 07 B3 00 A4 02 00 0D   ..-..L..L.......
1470  8B 1A 00 00 84 00 00 BB 2E 6C 10 83 18 A4 90 02   .........L......
1480  0D 8B 20 84 05 00 BB 20 8B 1E 00 83 02 BB 00 8B   .. .... ........
1490  30 83 04 09 BB 30 01 64 03 0B 8B 30 00 83 30 B3   0....0.D...0..0.
14A0  04 01 64 07 84 00 00 BB 04 8B 30 83 32 B3 30 8B   ..D.......0.2.0.
14B0  32 84 FF 4F 09 BB 32 01 64 03 0B 8B 32 84 00 00   2..O..2.D...2...
14C0  09 83 32 01 64 03 0B 8B 32 00 00 83 32 A4 05 00   ..2.D...2...2...
14D0  0D 8B 2C 00 00 00 00 00 00 00 00 00 00 00 00 00   ..,.............
14E0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
14F0  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
1500  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
1510  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
1520  26 00 10 82 1A BA 18 8A 08 82 08 B2 12 8A 12 00   _...............
1530  82 14 09 BA 12 01 64 03 0B 8A 12 00 82 12 B2 14   ......D.........
1540  01 64 07 84 00 00 BA 14 8A 12 00 82 08 BA 1C 8A   .D..............
1550  20 A4 01 00 82 24 BA 20 01 64 03 0B 8A 26 82 20    ....$. .D..._. 
1560  B2 24 01 64 03 0B 8A 26 82 26 7C 05 84 00 00 8A   .$.D..._._|.....
1570  20 84 00 00 8A 26 A2 06 84 FF 7F 0D 8A 16 09 00    ...._..........
1580  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
1590  00 00 0B BA 20 01 64 03 0B 8A 20 00 00 82 20 B2   .... .D... ... .
15A0  16 01 64 07 84 00 00 BA 16 8A 20 00 00 A2 20 82   ..D....... ... .
15B0  06 2C 0B 8A 0A 00 00 00 00 00 00 00 00 00 00 00   .,..............
15C0  82 22 09 BA 0A 01 64 03 0B 8A 0A 00 82 0A B2 22   ......D.........
15D0  01 64 07 84 00 00 BA 22 8A 0A 00 00 00 00 00 00   .D..............
15E0  A2 12 82 10 2C 0B 8A 0C 82 08 8A 1C A2 1E 84 FF   ....,...........
15F0  7F 0D 8A 16 09 82 08 B2 0A B2 0C 8A 20 0B BA 20   ............ .. 
1600  01 64 03 0B 8A 20 00 00 00 82 20 B2 16 01 64 07   .D... .... ...D.
1610  84 00 00 BA 16 8A 20 00 00 A2 20 82 1E 2C 0B 8A   ...... ... ..,..
1620  2A 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   *...............
```

```
1630   26 00 10 84 80 0C 8A 16 09 BA 2A 01 64 03 0B 8A   ..........*.D...
1640   2A 84 CB 0A 8A 16 82 2A B2 16 01 64 07 84 00 00   *......*...D....
1650   BA 16 8A 2A 00 00 00 00 00 00 00 00 00 00 00 00   ...*............
1660   84 00 00 BA 2A 8A 28 00 27 00 F0 82 2A 01 64 02   ....*.(.'...*.D.
1670   74 0F 84 00 00 8B 02 82 2A 0C 0C 0C 0C 8B 00 74   T.......*......T
1680   13 84 00 00 8B 00 82 28 0C 0C 0C 0C 8B 02 00 00   .......(........
1690   00 00 00 00 82 2C 0C 0C 0C 0C 8B 04 00 00 00 00   .....,..........
16A0   8B 06 27 00 0A C3 01 D4 80 7C 11 26 00 F0 84 00   ..'......|......
16B0   00 8A 00 8A 02 8A 06 5C 00 00 27 0A C4 FF CB 00   ..........'_....
16C0   C3 00 D4 80 7C FA CB 00 30 BC C9 02 4C 00 00 00   ....|...0...L...
16D0   00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
16E0   00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
16F0   00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
1700   00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
1710   00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
1720   00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00   ................
1730   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
1740   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
1750   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
1760   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
1770   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
1780   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
1790   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
17A0   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
17B0   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
17C0   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
17D0   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
17E0   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
17F0   FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF   ................
```

APPENDIX D

GAGE FACE GENERATION PROGRAM

LARGE GAGE FACE PROGRAM

```
C ********************************************************************
C *                                                                  *
C *                   LT PHILIP N. JOHNSON  U.S.N.                   *
C *                        17 JANUARY 1985                           *
C *               NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA            *
C *                                                                  *
C ********************************************************************
C
C CALL DISSPLA GRAPHICS PACKAGE
      REAL MIN,MAX,DIV,SDIV,A1,AR2,AR3,P1X,P1Y,P2X,P2Y,L1,L2,C1,C2
      REAL CAP,AR4,P3X,P3Y,XL1,XL2,F1
C     CALL TEK618
      CALL COMPRS
C     ******** START LEVEL 1 WORK *********
C     CALL NOBRDR
      CALL SWISSM
      CALL BASALF('STANDARD')
      CALL MIXALF('L/CSTD')
      CALL HWROT('MOVIE')
      CALL HWSCAL('SCREEN')
      CALL PAGE(8.5,11.0)
      W=5.75
      CALL AREA2D(W,9.25)
C     ******** START LEVEL 2 WORK *********
      CALL FRAME
      CALL SHDCHR(45.,1,.005,1)
      SCA = 1.0
      CALL HEIGHT(SCA/5.5)
      XL1=XMESS('OIL TEMPERATURE$',15)
      CALL MESSAG ('OIL TEMPERATURE$',15,(W/2.0)-(XL1/2),
     *8.7*SCA)
      XL2=XMESS('DEG. F$',6)
      CALL MESSAG ('DEG. F$',6,(W/2.0)-(XL2/2),7.2*SCA)
      CALL HEIGHT(SCA/7.0)
C     CALC NUMBER WIDTH
      XL3=XMESS('1234$',4)
      XL3=XL3/2.0
C     ******* START LEVEL 3 WORK ********
      MIN =0.0
      MAX= 300.0
```

```
      DIV= 50.0
      SDIV=5.0
      L1=((MAX-MIN)/DIV)
      L2=((MAX-MIN)/SDIV)
      C1=38.0
      C2=100.0
      VL=.5
      DO 100 I=1,L1+1
      CAP=DIV*(I-1)
      A1=(90+(C1/2.0))-(C1/L1*(I-1))
      AR2=A1/57.3
      P1X=((8.0*SCA*COS(AR2))+(W/2.0))
      P1Y=(8.0*SCA*SIN(AR2))
      AR3=(((90+(C2/2.0))+180.0)-(C2/L1*(I-1)))/57.3
      P2X=((VL*SCA*COS(AR3))+P1X)
      P2Y=((VL*SCA*SIN(AR3))+P1Y)
      AR4=AR3+3.14159
C     P3X=((.25*SCA*COS(AR4))+P1X)
      P3X=P1X
C     P3Y=((.25*SCA*SIN(AR4))+P1Y)
      P3Y=(.25*SCA)+P1Y
      ICAP=IFIX(CAP)
      XL3=XINT(ICAP)
      XL3=XL3/2.0
      CALL INTNO (ICAP,P3X-XL3,P3Y)
      CALL VECTOR (P1X,P1Y,P2X,P2Y,1100)
100   CONTINUE
      VL=.25
      DO 200 I=1,L2+1
      A1=(90+(C1/2.0))-(C1/L2*(I-1))
      AR2=A1/57.3
      P1X=((8.0*SCA*COS(AR2))+(W/2.0))
      P1Y=(8.0*SCA*SIN(AR2))
      AR3=(((90+(C2/2.0))+180.0)-(C2/L2*(I-1)))/57.3
      P2X=((VL*SCA*COS(AR3))+P1X)
      P2Y=((VL*SCA*SIN(AR3))+P1Y)
      CALL VECTOR (P1X,P1Y,P2X,P2Y,1100)
200   CONTINUE
      CALL ENDPL(0)
      CALL DONEPL
      STOP
      END
C ***********************************************************************

SMALL GAGEFACE PROGRAM

C ***********************************************************************
C *                                                                     *
```

```
C *                      LT PHILIP N. JOHNSON  U.S.N.                      *
C *                           15 FEBUARY 1985                              *
C *                 NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA                *
C *                                                                        *
C **************************************************************************
C
C CALL DISSPLA GRAPHICS PACKAGE
      REAL MIN,MAX,DIV,SDIV,A1,AR2,AR3,P1X,P1Y,P2X,P2Y,L1,L2,C1,C2
      REAL CAP,AR4,P3X,P3Y,XL1,XL2,F1
C     CALL TEK618
      CALL COMPRS
C     ******** START LEVEL 1 WORK *********
C     CALL NOBRDR
      CALL SWISSM
      CALL BASALF('STANDARD')
      CALL MIXALF('L/CSTD')
      CALL HWROT('MOVIE')
      CALL HWSCAL('SCREEN')
      CALL PAGE(8.5,11.0)
C     SCA = 1.4
      SCA = 1.0714
      W=1.75 *SCA
      YNEED = 2.0 *SCA
      CALL AREA2D(W,(2.0*YNEED))
C     ******** START LEVEL 2 WORK *********
      CALL FRAME
      CALL SHDCHR(45.,1,.005,1)
      SCALE = 8.0
      CALL HEIGHT(SCA/11.0)
      XL1=XMESS('MANUAL$',6)
      CALL MESSAG ('MANUAL$',6,(W/2.0)-(XL1/2),(2.05)*SCA)
C     XL2=XMESS('RPM$',3)
C     CALL MESSAG ('RPM$',3,(W/2.0)-(XL2/2),(0.9*SCALE)*SCA)
      CALL HEIGHT(SCA/11.0)
C     CALC NUMBER WIDTH
      XL3=XMESS('0$',1)
      XL3=XL3/2.0
C     ******* START LEVEL 3 WORK ********
      MIN =0.0
      MAX = 9.0
      DIV = 1.0
      SDIV = 0.5
      L1=((MAX-MIN)/DIV)
      L2=((MAX-MIN)/SDIV)
      C1=38.0
      C2=000.0
      YNEED=2.0
      VL=.125
```

```
      DO 100 I=1,L1+1
      CAP=DIV*(I-1)
      A1=(90+(C1/2.0))-(C1/L1*(I-1))
      AR2=A1/57.3
      P1X=((YNEED*SCA*COS(AR2))+(W/2.0))
      P1Y=(YNEED*SCA)
      AR3=(((90+(C2/2.0))+180.0)-(C2/L1*(I-1)))/57.3
      P2X=((VL*SCA*COS(AR3))+P1X)
      P2Y=((VL*SCA*SIN(AR3))+P1Y)
      AR4=AR3+3.14159
      P3X=((.25*SCA*COS(AR4))+P1X)
      P3Y=(-(.250*SCA*SIN(AR4))+P1Y)
      ICAP=IFIX(CAP)
      CALL INTNO (ICAP,P3X-XL3,P3Y)
      CALL VECTOR (P1X,P1Y,P2X,P2Y,1100)
100   CONTINUE
      VL=.065
      DO 200 I=1,L2+1
      A1=(90+(C1/2.0))-(C1/L2*(I-1))
      AR2=A1/57.3
      P1X=((YNEED*SCA*COS(AR2))+(W/2.0))
C     P1Y=(YNEED*SCA*SIN(AR2))
      P1Y=(YNEED*SCA)
      AR3=(((90+(C2/2.0))+180.0)-(C2/L2*(I-1)))/57.3
      P2X=((VL*SCA*COS(AR3))+P1X)
      P2Y=((VL*SCA*SIN(AR3))+P1Y)
      CALL VECTOR (P1X,P1Y,P2X,P2Y,1100)
200   CONTINUE
      CALL ENDPL(0)
      CALL DONEPL
      STOP
      END
```

APPENDIX E

DATA AQUISITION PROGRAM

HP 85 PROGRAM

READ 5

```
10]P(17),T(10),K(10),N(10),S(10)
20 PRINTER IS 10,120
30 CLEAR
40 DISP ENTER DATE:;
50 INPUT K1$
60 DISP ENTER TIME:;
70 INPUT K2$
80 DISP ENTER BAROMETRIC PRESS (IN.HG.);
90 INPUT P0
100 DISP
110 DISP ENTER FUEL SPECIFIC GRAVITY ;
120 INPUT S1
125 CLEAR
130 DISP
140 DISP ENTER UPPER ROTOMETER READING;
150 INPUT R2
160 DISP
170 DISP ENTER LOWER ROTOMETER READING;
180 INPUT R1
190 SETTIME 0,0
200 IMAGE K,3D.2D,K
210 IMAGE K,4D.D,K
220 IMAGE K,1D.4D,K
230 IMAGE K,5D.,K
240 ABORTIO 7
250 SET TIMEOUT 7;1000
260 OUTPUT 705 SCO 1-9 ,CHR$(13)
270 FOR I=1 TO 9
280 ENTER 705 USING %,K ; B$
31])
300 NEXT I
310 ABORTIO 7
320 SET TIMEOUT 7;1000
330 OUTPUT 705 SCO 10-16 ,CHR$(13)
340 FOR J=1 TO 7
350 ENTER 705 USING %,K ; C$
41])
370 NEXT J
```

```
380 ABORTIO 7
390 REM SUBROUTINE FOR TYPE T
400 FOR I=0 TO 9
410 GOSUB 450
420 T(I)=T0
430 NEXT I
440 GOTO 590
450 REM
460 OUTPUT 709 ;AC,I
470 M0=.1008609
480 M1=25727.94369
490 M2=-767345.8295
500 M3=78025595.81
510 M4=-924786589
520 M5=697688000000
530 M6=-2.66192E13
540 M7=3.94078E14
550 ENTER 709 ; V
560 T0=M0+V*(M1+V*(M2+V*(M3+V*(M4+V*(M5+V*(M6+V*M7))))))
570 T0=9/5*T0+32
580 RETURN
590 REM INPUT TYPE K
600 FOR I=10 TO 19
610 GOSUB 650
620 K(I-9)=K0
630 NEXT I
640 GOTO 800
650 REM
660 L0=.226584602
670 L1=24152.109
680 L2=67233.4248
690 L3=2210340.682
700 L4=-860963914.9
710 L5=48350600000
720 L6=-1.18452E12
730 L7=1.3869E13
740 L8=-6.33708E13
750 OUTPUT 709 ;AC,I
760 ENTER 709 ; V
770 K0=L0+V*(L1+V*(L2+V*(L3+V*(L4+V*(L5+V*(L6+V*(L7+V*L8)))))))
780 K0=9/5*K0+32
790 RETURN
800 REM SPEEDS ETC.
810 FOR I=20 TO 28
820 OUTPUT 709 ;AC,I
830 ENTER 709 ; N(I-19)
840 NEXT I
850 REM S(1)=DYNO SPEED
```

```
860 S(1)=0+N(1)*652.728191
870 REM S(2)=TURBINE SPEED
880 S(2)=16143.31+N(2)*3778
890 REM S(4)=DYNO TORQUE
900 S(4)=N(4)*59.254138
910 REM S(6)=FUEL FLOW
920 S(6)=100+N(6)*110
930 REM S(3)=DYNO SPEED
940 S(3)=N(3)*820
950 REM S(5)=DYNO POWER
960 S(5)=N(5)*10
970 PRINT ***************************************************************
980 PRINT                      TURBINE ANALYSIS PROGRAM
990 PRINT ***************************************************************
1000 PRINT
1010 PRINT DATE: ;K1$
1020 PRINT
1030 PRINT TIME: ;K2$
1040 PRINT
1050 PRINT
1060 PRINT
1070 PRINT PRESSURES
1080 PRINT
1090 PRINT USING 200 ; BAROMETERIC PRESSURE =;P0; IN.HG.
1100 PRINT USING 200 ; CELL PRESSURE FRONT = ,P(15), IN.H2O
1110 PRINT USING 200 ; CELL PRESSURE REAR = ,P(14), IN.H2O
1120 PRINT USING 200 ; CELL PRESSURE AVERAGE = ,(P(15)+P(14))/2, IN.H2O
1130 PRINT USING 200 ; AIRFLOW BELL PRESSURE RIGHT = ,P(16), IN.H2O
1140 PRINT USING 200 ; AIRFLOW BELL PRESSURE LEFT = ,P(11), IN.H2O
1150 PRINT USING 200 ; AIRFLOW BELL PRESSURE AVERAGE = ,(P(11)+P(16))/2, IN.H2O
1160 PRINT USING 200 ; COMPRESSOR DISCHARGE PRESSURE RIGHT = ,P(2), IN.HG
1170 PRINT USING 200 ; COMPRESSOR DISCHARGE PRESSURE LEFT = ,P(5), IN.HG
1180 PRINT USING 200 ; COMPRESSOR DISCHARGE PRESSURE AVERAGE = ,(P(5)+P(2))/2, I
1190 PRINT USING 200 ; NOZZLE BOX PRESSURE = ,P(1), IN.HG
1200 PRINT
1210 PRINT TEMPERATURE
1220 PRINT
1230 PRINT USING 210 ; COMPRESSOR INLET TEMP. A = ,T(0), DEG. F
1240 PRINT USING 210 ; COMPRESSOR INLET TEMP. B = ,T(1), DEG. F
1250 PRINT USING 210 ; COMPRESSOR INLET TEMP. C = ,T(2), DEG. F
1260 PRINT USING 210 ; COMPRESSOR INLET TEMP. D = ,T(3), DEG. F
1270 PRINT USING 210 ; COMPRESSOR INLET TEMP. AVERAGE = ,(T(0)+T(1)+T(2)+T(3))/4
1280 PRINT USING 210 ; COMPRESSOR DISCHARGE TEMP. RIGHT A = ,T(4), DEG. F
1290 PRINT USING 210 ; COMPRESSOR DISCHARGE TEMP. LEFT A = ,T(5), DEG. F
1300 PRINT USING 210 ; COMPRESSOR DISCHARGE TEMP. RIGHT B = ,T(6), DEG. F
1310 PRINT USING 210 ; COMPRESSOR DISCHARGE TEMP. LEFT B = ,T(7), DEG. F
1320 PRINT USING 210 ; COMPRESSOR DISCHARGE TEMP. AVERAGE = ,(T(4)+T(5)+T(6)+T(7
1330 PRINT USING 210 ; FUEL TEMP = ,T(8), DEG. F
```

```
1340 PRINT USING 210 ; TURBINE INLET TEMP. RIGHT A = ,K(1), DEG. F
1350 PRINT USING 210 ; TURBINE INLET TEMP. LEFT A = ,K(2), DEG. F
1360 PRINT USING 210 ; TURBINE INLET TEMP. RIGHT B = ,K(3), DEG. F
1370 PRINT USING 210 ; TURBINE INLET TEMP. LEFT B = ,K(4), DEG. F
1380 PRINT USING 210 ; TURBINE INLET TEMP. AVERAGE = ,(K(1)+K(2)+K(3)+K(4))/4, D
1390 PRINT USING 210 ; EXHAUST TEMP. RIGHT A = ,K(5), DEG. F
1400 PRINT USING 210 ; EXHAUST TEMP. LEFT A = ,K(6), DEG. F
1410 PRINT USING 210 ; EXHAUST TEMP. RIGHT B = ,K(7), DEG. F
1420 PRINT USING 210 ; EXHAUST TEMP. LEFT B = ,K(8), DEG. F
1430 PRINT USING 210 ; EXHAUST TEMP. AVERAGE = ,(K(5)+K(6)+K(7)+K(8))/4, DEG. F
1440 PRINT
1450 PRINT SPEEDS ETC.
1460 PRINT
1470 PRINT USING 210 ; UPPER ROTOMETER = ,R2,
1480 PRINT USING 210 ; LOWER ROTOMETER = ,R1,
1490 PRINT USING 220 ; SPECIFIC GRAVITY = ,S1,
1500 PRINT USING 230 ; TURBINE SPEED = ,S(2), RPM
1510 PRINT USING 230 ; DYNAMOMETER SPEED = ,S(1), RPM
1520 PRINT USING 230 ; DYNAMOMETER TORQUE = ,S(4), FT-LB
1530 PRINT USING 230 ; FUEL FLOW SENSOR = ,S(6), UPPER ROTOMETER
1540 REM S(2) = COMPRESSOR SPEED
1550 REM S(1) = DYNAMOMETER SPEED
1560 REM T(0) = INLET TEMP 1
1570 REM T(1) = INLET TEMP 2
1580 REM T(2) = INLET TEMP 3
1590 REM T(3) = INLET TEMP 4
1600 REM T(4) = COMPRESSOR DISCHARGE RIGHT TEMP A
1610 REM T(5) = COMPRESSOR DISCHARGE LEFT TEMP A
1620 REM T (6) = COMPRESSOR DISCHARGE RIGHT TEMP B
1630 REM T(7) = COMPRESSOR DISCHARGE LEFT TEMP B
1640 REM T (8) = FUEL TEMP
1650 REM K(1) = TURBINE INLET RIGHT TEMP A
1660 REM K(2) = TURBINE INLET LEFT TEMP A
1670 REM K(3) = TURBINE INLET RIGHT TEMP B
1680 REM K(4) = TURBINE INLET LEFT TEMP B
1690 REM K(5) = EXHAUST RIGHT TEMP A
1700 REM K(6) = EXHAUST LEFT TEMP A
1710 REM K(7) = EXHAUST RIGHT TEMP B
1720 REM K(8) = EXHAUST LEFT TEMP B
1730 REM P(15) = CELL PRESS FORWARD
1740 REM P(14) = CELL PRESS REAR
1750 REM P(16) = AIR FLOW NOZZLE PRESS RIGHT
1760 REM P(11) = AIR FLOW NOZZLE PRESS LEFT
1770 REM P(2) = COMPRESSOR DISCHARGE PRESS RIGHT
1780 REM P(5) = COMPRESSOR DISCHARGE PRESS LEFT
1790 REM P(1) = NOZZLE BOX PRESSURE
1800 REM S(4) = TORQUE
1810 REM R0 = FUEL FLOW RATE
```

```
1820 REM R1 = LOWER ROTOMETER READING
1830 REM R2 = UPPER ROTOMETER READING
1840 REM S1 = SPECIFIC GRAVITY OF FUEL
1850 REM P0 = ATM. PRESSURE
1860 REM
1870 REM CALCULATED VALUES
1880 REM
1890 REM T0 = AVERAGE INLET TEMP
1900 REM D0 = THETA CORRECTION FACTOR
1910 REM D1 = DELTA CORRECTION FACTOR
1920 REM P9 = CORRECTED TURBINE INLET PRESSURE
1930 REM A1 = API AT 60 DEG
1940 REM S2 = CORRECTED SPECIFIC GRAVITY TO 60 DEG F.
1950 REM Q2 = LOWER HEATING VALUE
1960 REM Q3 = CORRECTED TORQUE
1970 REM N3 = CORRECTED COMPRESSOR SPEED
1980 REM N4 = CORRECTED DYNAMOMETER SPEED
1990 REM B1 = CORRECTED BRAKE HORSE POWER
2000 REM M1 = MASS FLOW RATE LOWER FLOAT
2010 REM M2 = MASS FLOW RATE UPPER FLOAT
2020 REM C1 = ROTOMETER CONVERSION FACTOR
2030 REM M3 = CORRECTED MASS FLOW RATE UPPER FLOAT
2040 REM M4 = CORRECTED MASS FLOW RATE LOWER FLOAT
2050 REM M5 = CORRECTED MASS FLOWRATE
2060 REM B2 = BRAKE SPECIFIC FULE CONSUMPTION
2070 REM B3 = BRAKE THERMAL EFFICIENCY
2080 REM E1 = AVERAGE INLET BELL THROAT PRESS
2090 REM E2 = INLET BELL THROAT PRESS
2100 REM D2 = DELTA PRESSURE IN THROAT
2110 REM M6 = MASS FLOW RATE OF AIR
2120 REM M7 = CORRECTED MASS FLOW RATE OF AIR
2130 REM A2 = AIR FUEL RATIO
2140 REM K9 = AVE EXHAUST TEMP
2150 REM O1 = AVE COMPRESSOR DISCHARGE PRESS
2160 REM O2 = PRESSURE RATIO
2170 REM O3 =IDEAL THERMAL EFFICIENCY
2180 REM O4 = AVE COMPRESSOR DISCHARGE TEMP
2190 REM O5 = AVE TURBINE INLET TEMP
2200 T1=84.8
2210 T2=88
2220 T3=91.7
2230 T4=80.4
2240 P0=29.7326
2250 P1=.1
2260 S1=.8546
2270 T9=71
2280 P2=.1
2290 Q1=129.7
```

```
2300 N1=27000
2310 N2=1500
2320 R1=99
2330 R2=204
2340 P3=10.6
2350 P4=10.6
2360 P5=26.5
2370 P6=26.5
2380 K5=524
2390 K6=508
2400 K7=530
2410 K8=502
2420 K1=1200
2430 K2=1220
2440 K3=1190
2450 K4=1200
2460 T5=234.4
2470 T6=227.6
2480 T7=232
2490 T8=234
2500 REM CALCULATE CORRECTION FACTORS
2510 T0=(T(0)+T(1)+T(2)+T(3))*.25+460
2520 D0=T0/520
2530 P9=P0*(14.696/29.92)+(P(15)+P(14))/2*(14.696/406.92)
2540 D1=P9/14.696
2550 REM CALCULATE LOWER HEATING VALUE
2560 S2=S1+(T(8)-60)/3600
2570 A1=141.5/S2-131.5
2580 Q2=16380+60*A1
2590 REM CALCULATE CORRECTED TORQUE
2600 Q3=S(4)/D1
2610 REM CALCULATE CORRECTED COMPRESSOR SPEED
2620 N3=S(2)/SQR(D0)
2630 REM CALCLUATE CORRECTED DYNANOMETER SPEED
2640 N4=S(1)/SQR(D0)
2650 REM CALCULATE CORRECTED BRAKE HORSEPOWER
2660 B1=2*3.141592*Q1*S(1)/(33000*D1*SQR(D0))
2670 REM CALCULATE MASS FLOW RATE OF FUEL
2680 M2=.607954*R2-4.627907
2690 M1=1.17442*R1-8.556818
2700 C1=SQR((7.82-S1)*S1)/SQR((7.82-.8637)*.8637)
2710 M3=C1*M1
2720 M4=C1*M2
2730 M5=(M3+M4)/2/(D1*SQR(D0))
2740 REM CALCULATE BRAKE SPECIFIC FUEL CONSUMPTION
2750 B2=M5/B1
2760 REM CALCULATE BRAKE THERMAL EFFICIENCY
2770 B3=2545/(B2*Q2)
```

```
2780 REM CALCULATE MASS FLOW RATE OF AIR
2790 E1=-((P(16)+P(11))/2)
2800 E2=P0*(14.696/29.92)-E1*(14.696/406.92)
2810 D2=P9-E2
2820
M6=8.02*.98*P9*21.8956/SQR(53.34*T0)*SQR(D2/P9-1.5/1.4*(D2/P9)   2)
2830 M7=M6*SQR(D0)/D1
2840 REM CALCULATE AIR/FUEL RATIO
2850 A1=M7*3600/M5
2860 REM CALCULATE EXAUST GAS TEMP
2870 K9=(K(5)+K(6)+K(7)+K(8))/4+460
2880 REM CALCULATE PRESSURE RATIO
2890 O1=P9+(P(5)+P(2))/2*14.696/29.92
2900 O2=O1/P9
2910 REM CALCULATE COMPRESSOR DISCHARGE TEMP
2920 O4=.25*(T(4)+T(5)+T(6)+T(7))+460
2930 REM CALCULATE TURBINE INLET TEMP
2940 O5=(K(1)+K(2)+K(3)+K(4))/4+460
2950 REM CALCULATE IDEAL THERMAL EFFICIENCY
2960 O3=1-1/O2                    (.4/1.4)
2970 PRINT
2980 PRINT ANALYSIS
2990 PRINT
3000 PRINT USING 210 ; COMPRESSOR INLET TEMP. = ,T0, DEG. R.
3010 PRINT THETA = ;D0
3020 PRINT USING 200 ; COMPRESSOR INLET PRESSURE = ,P9, PSIA
3030 PRINT DELTA = ;D1
3040 PRINT USING 230 ; LOWER HEATING VALUE = ,Q2, BTU/LBM
3050 PRINT USING 230 ; CORRECTED TORQUE = ,Q3, FT-LB
3060 PRINT USING 230 ; CORRECTED COMPRESSOR SPEED  = ,N3, RPM
3070 PRINT USING 230 ; CORRECTED DYNAMOMETER SPEED = ,N4, RPM
3080 PRINT USING 230 ; CORRECTED BRAKE HORSE POWER = ,B1, HP
3090 PRINT USING 200 ; CORRECTED MASS FUEL FLOW = ,M5, LBM/HR
3100 PRINT USING 210 ; BRAKE SPECIFIC FUEL CONSUMPTION = ,B2, LBM/HP-HR
3110 PRINT USING 200 ; BRAKE THERMAL EFF. = ,B3*100, PRECENT
3120 PRINT USING 200 ; CORRECTED MASS AIR FLOW = ,M7, LBM/SEC
3130 PRINT AIR FUEL RATIO = ;A1
3140 PRINT USING 210 ; AVERAGE EXAUST TEMP. = ,K9, DEG R.
3150 PRINT COMPRESSOR PRESSURE RATIO  = ;O2
3160 PRINT USING 210 ; COMPRESSOR  DISCHARGE TEMP. = ,O4, DEG. R.
3170 PRINT USING 210 ; AVERAGE TURBINE INLET TEMP. = ,O5, DEG. R.
3180 PRINT USING 200 ; IDEAL COMPRESSOR EFF. = ,O3*100, PERCENT
3190 GOTO 125
```

SAMPLE OUTPUT

```
                                TURBINE ANALYSIS PROGRAM
*********************************************************************************

DATE: 6 JUNE 1985

TIME: 1300


PRESSURES

BAROMETERIC PRESSURE = 30.13 IN.HG.
CELL PRESSURE FRONT =   -.04 IN.H2O
CELL PRESSURE REAR =   -.07 IN.H2O
CELL PRESSURE AVERAGE =   -.06 IN.H2O
AIRFLOW BELL PRESSURE RIGHT =  -9.62 IN.H2O
AIRFLOW BELL PRESSURE LEFT =  -9.53 IN.H2O
AIRFLOW BELL PRESSURE AVERAGE =  -9.58 IN.H2O
COMPRESSOR DISCHARGE PRESSURE RIGHT =  22.82 IN.HG
COMPRESSOR DISCHARGE PRESSURE LEFT =  22.66 IN.HG
COMPRESSOR DISCHARGE PRESSURE AVERAGE =  22.74 IN.HG
NOZZLE BOX PRESSURE =  22.41 IN.HG

TEMPERATURE

COMPRESSOR INLET TEMP. A =   68.9 DEG. F
COMPRESSOR INLET TEMP. B =   70.8 DEG. F
COMPRESSOR INLET TEMP. C =   71.6 DEG. F
COMPRESSOR INLET TEMP. D =   72.4 DEG. F
COMPRESSOR INLET TEMP. AVERAGE =   70.9 DEG. F
COMPRESSOR DISCHARGE TEMP. RIGHT A =  201.6 DEG. F
COMPRESSOR DISCHARGE TEMP. LEFT A =  203.3 DEG. F
COMPRESSOR DISCHARGE TEMP. RIGHT B =  196.7 DEG. F
COMPRESSOR DISCHARGE TEMP. LEFT B =  202.8 DEG. F
COMPRESSOR DISCHARGE TEMP. AVERAGE =  201.1 DEG. F
FUEL TEMP =   68.1 DEG. F
TURBINE INLET TEMP. RIGHT A = 1181.4 DEG. F
TURBINE INLET TEMP. LEFT A = 1341.9 DEG. F
TURBINE INLET TEMP. RIGHT B = 1200.7 DEG. F
TURBINE INLET TEMP. LEFT B = 1345.7 DEG. F
TURBINE INLET TEMP. AVERAGE = 1267.4 DEG. F
EXHAUST TEMP. RIGHT A =  902.6 DEG. F
EXHAUST TEMP. LEFT A =  947.0 DEG. F
EXHAUST TEMP. RIGHT B =  893.7 DEG. F
EXHAUST TEMP. LEFT B =  930.0 DEG. F
EXHAUST TEMP. AVERAGE =  918.3 DEG. F
```

SPEEDS ETC.

UPPER ROTOMETER = 185.0
LOWER ROTOMETER =   90.0
SPECIFIC GRAVITY = .8650
TURBINE SPEED = 24881. RPM
DYNAMOMETER SPEED =   985. RPM
DYNAMOMETER TORQUE =   138. FT-LB
FUEL FLOW SENSOR =   106. UPPER ROTOMETER

ANALYSIS

COMPRESSOR INLET TEMP. = 530.9 DEG. R.
THETA = 1.02097892304
COMPRESSOR INLET PRESSURE = 14.60 PSIA
DELTA = .993601469311
LOWER HEATING VALUE = 18398. BTU/LBM
CORRECTED TORQUE =   139. FT-LB
CORRECTED COMPRESSOR SPEED = 24624. RPM
CORRECTED DYNAMOMETER SPEED =   975. RPM
CORRECTED BRAKE HORSE POWER =   24. HP
CORRECTED MASS FUEL FLOW = 112.58 LBM/HR
BRAKE SPECIFIC FUEL CONSUMPTION =   4.6 LBM/HP-HR
BRAKE THERMAL EFF. =   2.98 PRECENT
CORRECTED MASS AIR FLOW =   2.30 LBM/SEC
AIR FUEL RATIO = 73.5663700269
AVERAGE EXAUST TEMP. = 1378.3 DEG R.
COMPRESSOR PRESSURE RATIO = 1.76492110916
COMPRESSOR DISCHARGE TEMP. = 661.1 DEG. R.
AVERAGE TURBINE INLET TEMP. = 1727.4 DEG. R.
IDEAL COMPRESSOR EFF. = 14.98 PERCENT

APPENDIX F
DIGITAL TO ANALOG INTERFACE

The digital to analog interface accomplishes the conversion of digital signals to analog voltages, decodes bus addresses, and provides computer and actuator signal isolation. The design requirements dictated the need for a design having a minimum of three independent analog output ports. The precision required varied from the throttle output port, which needs 12 bit or 4096 count accuracy, to the valves which only required 8 bit or 256 count accuracy. For simplicity the interface card was designed for 12 bit accuracy on all ports.

The interface uses a 74LS139 to decode addresses F000 to F008 from the bus [Ref. 6]. Three resident DAC1230's are connected directly to the data bus and receive information in two successive 8 bit transfers. Address F006 is used to trigger all output ports and exicute a transfer of digital information to the DAC. The output is buffered by a MC3403 operational amplifier which isolates the DAC's from the environment. A gain adjustment controls the voltage output of an LM337 which is used as a reference voltage for all DAC's. This gain pot permits the adjustment of the range of voltage corresponding to a 0 to 4095 change in input, and provides approximately 1 to 10 volt full scale output. A zero adjustment provides zeroing capability to the DAC's output and may be adjusted from -0.1 volts to 2 volts.

Figure F.1 shows the general layout of the card. The adjustment pots and test connections were placed at the bottom edge of the card to permit adjustment while in operation. Figure F.2 show the wiring of one of three DAC's. Wiring of other two DAC's are similar.

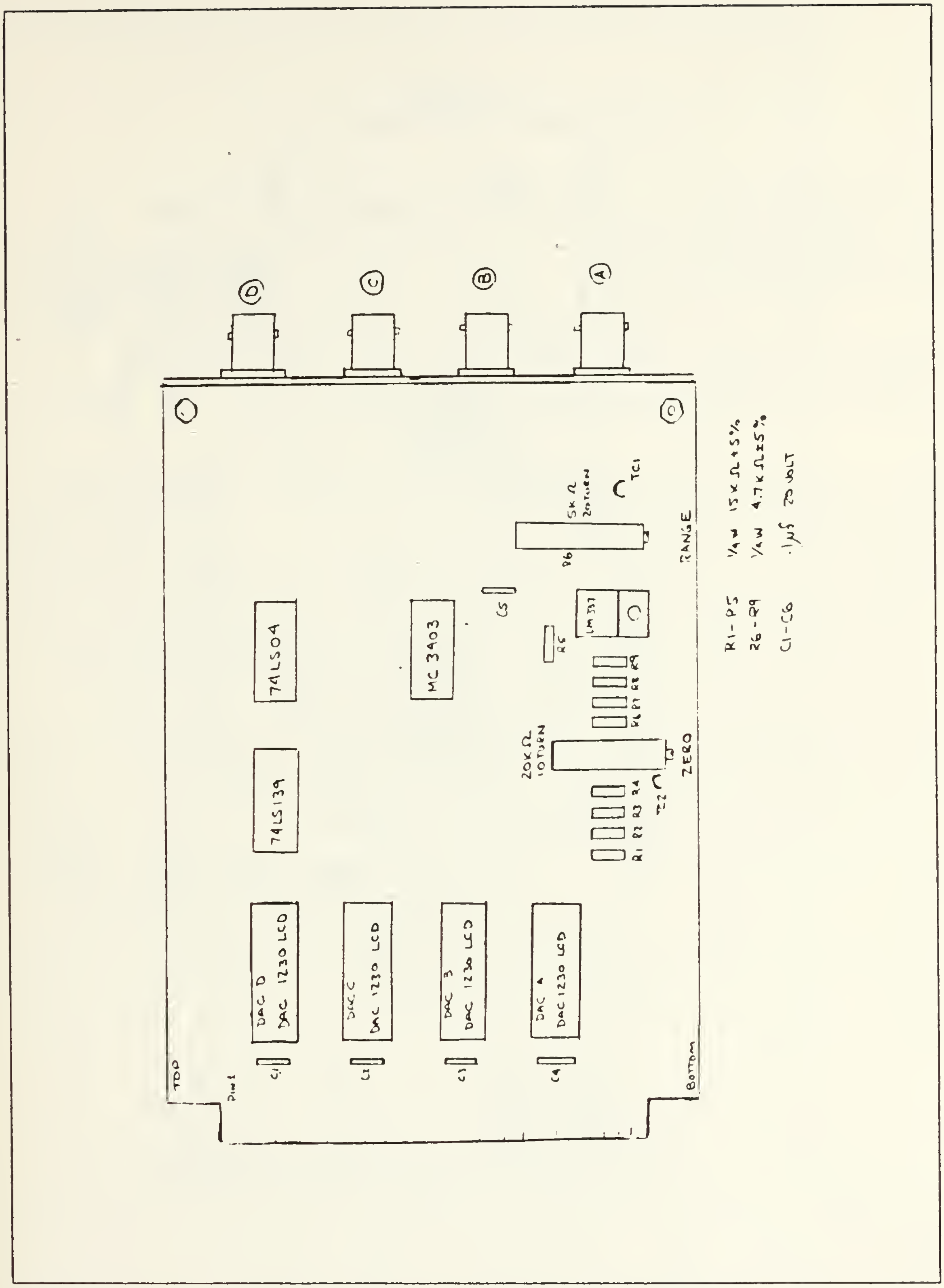

Figure F.1 Digital to Analog Card Layout

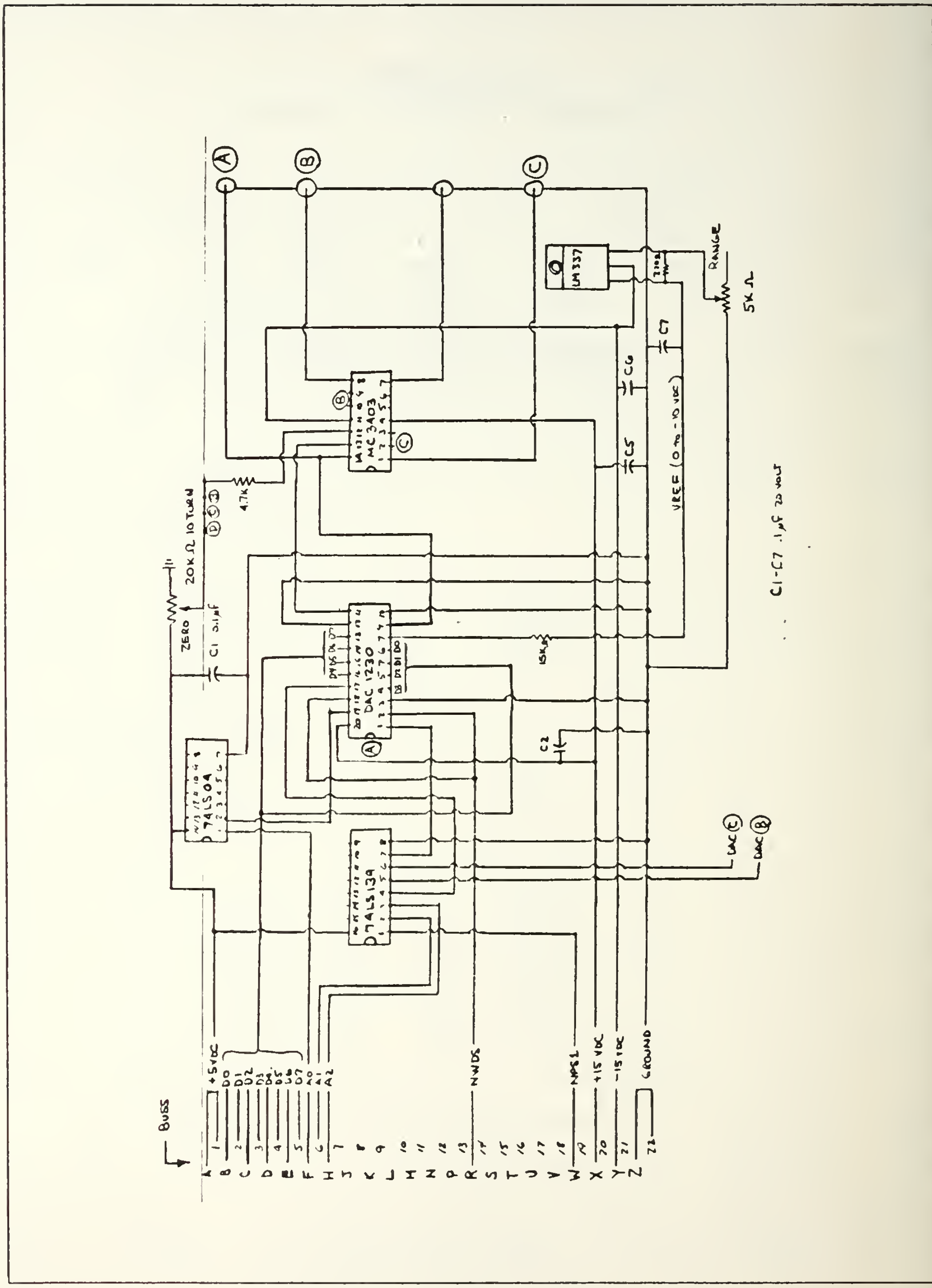

Figure F.2 Digital to Analog Wiring Diagram

APPENDIX G
VALVE POSITIONER CONTROLLER

The valve position controller utilizes a feedback potentiometer, operational amplifier, and solid state relays to apply voltage to the motor windings phased in such a way as to move the motor in the desired direction.

The desired valve position has two possible inputs depending on the position of the selector switch (figure G.1)

If the selector switch is in the computer position, the input voltage is provided by the DAC's of the microprocessor interface board. If the selector switch is in the manual position, the desired valve position is provided by an adjustable voltage bridge. This bridge is a variable resistor of 20k ohm resistance connected across +5 volts and ground. It's output therefore may be varied between 0 and +5 volts. From the selector switch the desired valve position in the form of a voltage between 0 and 5 volts which is compaired with actual valve position. Actual valve position is generated in the same maner as manual desired valve position except the potentiometer is connected to the valve via a gearing arrangement. This position feedback system measures valve position in the form of a voltage, 0 volts corresponding to fully closed and +5 volts to fully open. This voltage is also fed to a voltage follower circuit which is used to drive a meter which mimics valve position.

Both the desired position from the selector switch and the actual position from the valves are fed into an operational amplifier which has a resistor network to provide windowing in order to prevent valve oscilation. The output of the operational amplifiers drive transistors which in turn drive

a light emitting diode and a solid state relay which close to provide 120 volt alternating current to a resistor and capacitor network. Thus the valve is turned in the correct direction [Ref. 8].

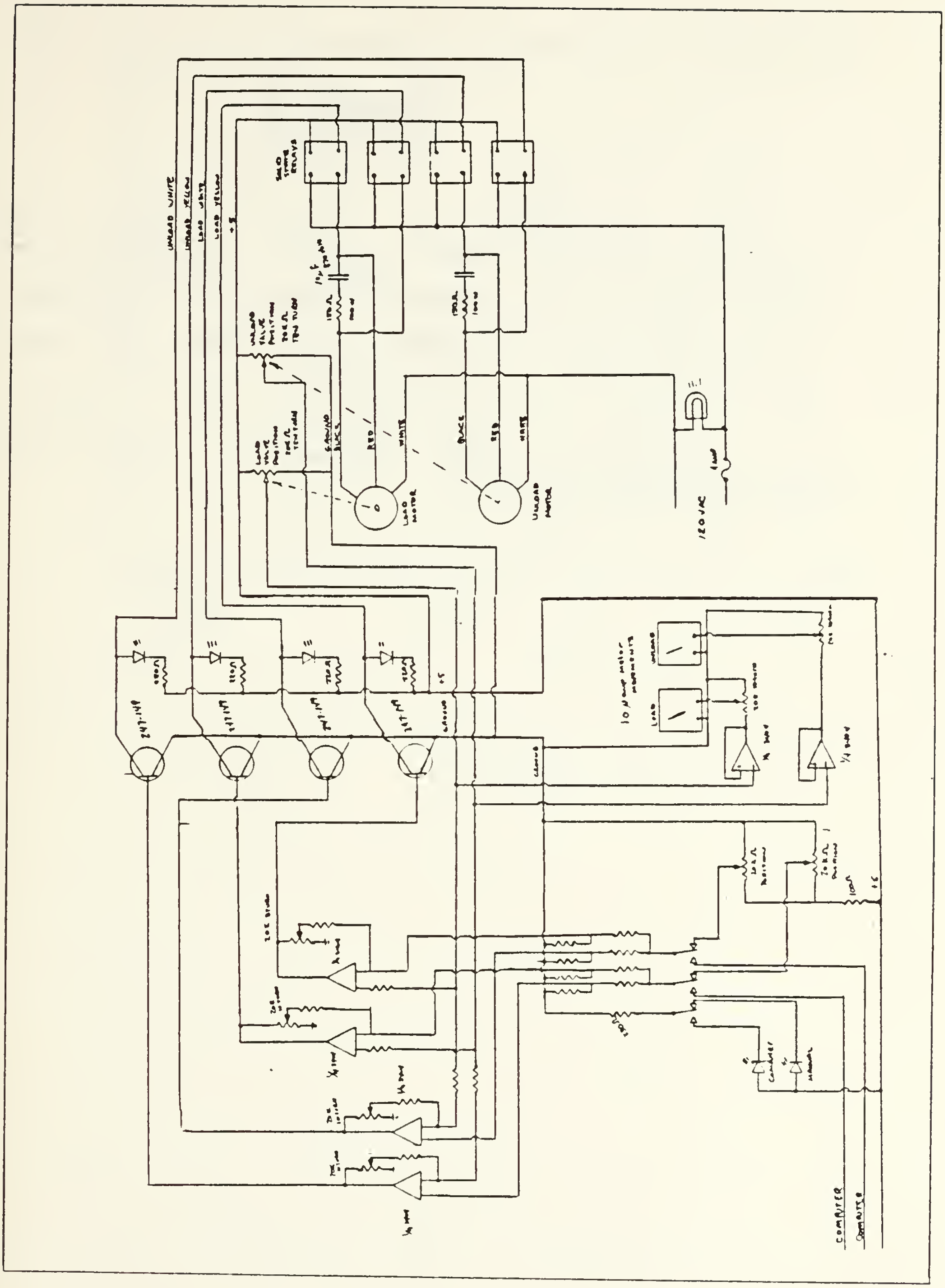

Figure G.1 Valve Positioner Circuit.

APPENDIX H
POWER SUPPLY

The power supply used for the operators panel is a converted 28 volt power supply. Printed circuit board traces were cut and regulators installed to provide ± 15 and ± 18 volts. An additional transformer was installed to provide +5 volts. Each supply is capable of delivering 1 amp of current at the voltage specified. Component locations are shown in figure H.1 and the circuit schematic is shown in figure H.2

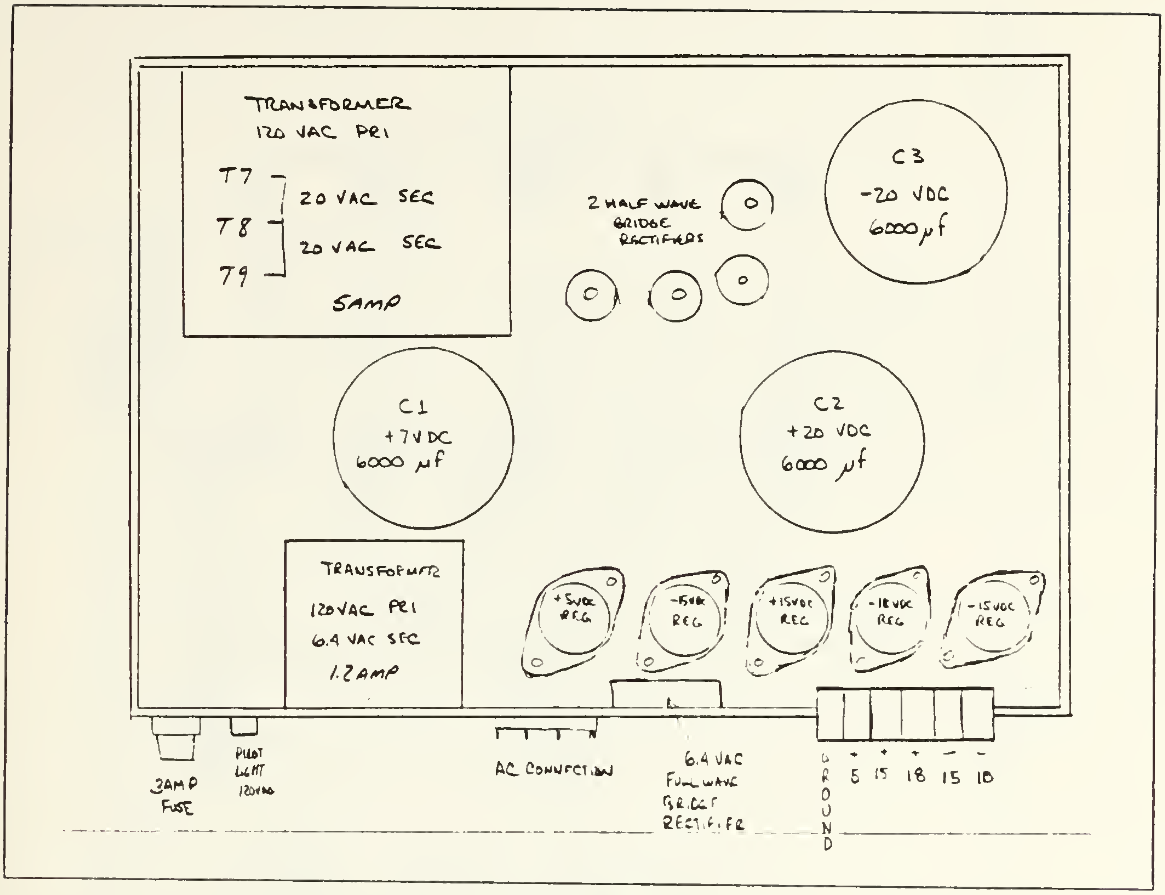

Figure H.1   Power supply layout.

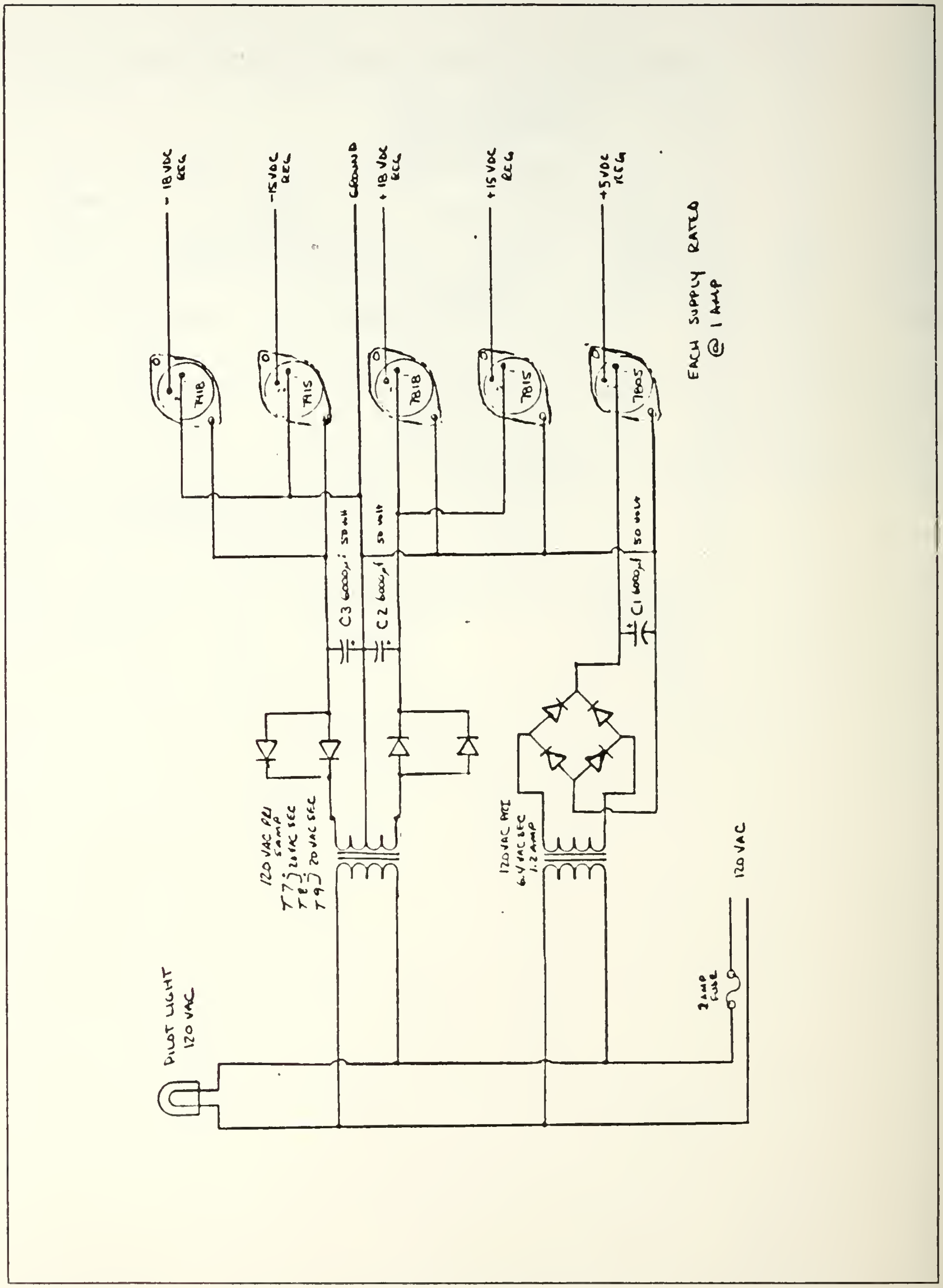

Figure H.2   Power Schematic Layout

APPENDIX I

TURBINE OPERATING PROCEDURES

TURBINE START CHECKLIST

1. Align and start low pressure air compressor. (a minimum of 50 psig is required for turbine operation.)
2. Check in-ground fuel storage tank for adequate fuel. (a minimum of 50 gallons is required to prevent loss of suction on transfer pump.) Note: The sounding rod is stored behind the student gage panel.
3. Close power breaker for fuel transfer pump, turn on fuel transfer switch located on operators panel, and push start button on controller box. Verify that fuel transfer pump maintains a normal level in head tank.
4. Turn on power to the student instrument panel (plug inside).
5. Turn on control computer and terminal.
6. Turn on computer acquisition equipment, and load acquisition program.
7. Insure 120 vac and 24 vdc fuel trips, glow coil, igniter and starter switches are in the off position.
8. Turn 24 vdc power on. (note: damper position indicators should illuminate.)
9. Turn dynamometer flow valve control knobs to the full counter clockwise position.
10. Place both dynamometer and gas turbine controllers in manual control.
11. Turn 120 vac power and blower on. (note that instruments should respond to their current sensed values and valve motors should be at rest.)
12. Turn test cell lighting on using wall switch adjacent to door.

13. Check module for loose debris, check turbine for correct oil level and check both turbine and dynamometer for any loose sensing or control connections.

14. Open the following valves located behind the dynamometer. a) Lube oil cooler water supply valve. b) Fuel oil supply valve. c) Air supply valve. d) Dynamometer cooling water supply valve.

15. Adjust dynamometer shell pressure to 4 psig.

16. Verify dynamometer load cell pressure regulator is set at 37 psig.

17. Open inlet and exhaust dampers, and insure front and front-side doors are shut tightly.

18. Exit and shut rear cell door.

19. Don protective hearing gear.

20. Review operating parameters for turbine and dynamometer. a) Dynamometer temp should not exceed 140 deg. f. b) Dynamometer speed should not exceed 3300 rpm. c) Dynamometer should not be run empty. d) Dynamometer shell pressure should not exceed 6 psig. e) Dynamometer speeds below 960 rpm may not be obtainable at high compressor speeds. f) Turbine oil temp should not exceed 220 deg.f. g) Turbine speed should not exceed 36500 rpm. h) Turbine speed must be maintained above 17000 rpm. i) turbine exhaust temp must not exceed 1350 deg f. j) Rapid accelerations/deccelerations should be avoided. k) Minimum oil pressure is 40 psig. l) Maximum starter operation is 30 seconds.

21. Remember there are no safety trips on this equipment and the operator is responsible for keeping the equipment within safe operating limits.

22. Turbine start procedure. a) Verify throttle control by cycling actuator then set throttle at 1.5. (this corresponds to 20000 rpm idle) b) Cycle dynamometer valves to verify control then open load valve to position 5 for 5 seconds, then close. c) Turn on glow coil,

igniters and 120 vac fuel solenoid and depress the master start button for 5 seconds, then switch on starter. d) When turbine speed reaches 5000 rpm turn on 24 vdc fuel solenoid, turbine speed should continue to rise, at 15000 rpm release master start button and turn off starter, glow coil, and igniters, turbine speed of 20000 rpm should be attained within 5 seconds of DC fuel valve opening. e) Should turbine fail to start or is slow in acceleration to 20000 rpm (greater than 5 seconds), close fuel trips and turn off igniters and glow coils but continue to motor turbine for 15 seconds. Secure engine and determine cause of failure to start befort attempting to start again. (Note: a minimum of 15 minutes is required to allow starter to cool between starts.) f) When turbine reaches idle verify operating parameters are within limits, especially. 1) Dynamometer speed. 2) Oil pressure. 3) Alternator current. 4) Fuel pressure. g) View cell form operating window and check for abnormalities.

23. Enter turbine speed and dynamometer selection on control terminal (note flashing internal led indicates correct computer operation.)
24. Switch dynamometer control form manual to computer on operators console and observe that speed attains set point.
25. Manually bring turbine speed to slightly above the selected set point and observe computer throttle position decreases from full throttle, when manual and computer signals are matched, switch throttle to computer control.
26. To select new operating speeds simply depress the white reset button on the microprocessor controller. (Note: while new values are being entered, dynamometer valves are closed and throttle remains fixed.)

27. Should the operator exit the program abnormally the turbine should be taken back into manual control.

28. Instabilities in dynamometer operation may exist at high operating speeds and low loads, should this occur adjustment of the flow control valve located near the dynamometer heat exchanger may be necessary. This flow control valve must br opened when operating dynamometer above 150 horsepower.

TURBINE SHUTDOWN CHECKLIST

1. Bring turbine to 20000 rpm idle for 1 minute.

2. Place both turbine and dyamometer in manual control.

3. Unload dynamometer completely.

4. Secure both 24 vdc and 120 vac fuel trips.

5. Enter test cell and close the following valves. a) Lube oil cooler water supply valve. b) Fuel oil supply valve. c) Air supply valve. d) Dynamometer cooling water supply valve.

6. Close supply and exhaust dampers.

7. Exit and close rear cell door.

8. Turn off power to data acquisition equipment.

9. Turn off (unplug) student instrument panel.

10. Open fuel transfer pump breaker.

11. Turn off computer controller and terminal.

12. Turn off all power to operators panel except blower power.

13. Secure blower 20 minutes after shutdown.

14. Cover equipment and extinguish lighting.

APPENDIX J

STUDENT PANEL INSTRUMENTS

GAS GENERATOR SPEED NEWPORT (DIGITAL COUNTER) MODEL 6130A 0 TO 99,999 RPM RESOLUTION +/- 1 RPM INTERGRATED OVER 10 SECONDS SERIAL # 9020267 - 25

DYNAMOMETER SPEED NEWPORT (DIGITAL COUNTER) MODEL 6130A 0 TO 9999 RPM RESOLUTION +/- 1 RPM INTERGRATED OVER 1 SECOND SERIAL # 9041670 - 25

TYPE "K" DIGITAL PYROMETER NEWPORT MODEL 267-B KF-1 -225 TO +2500 DEG. F RESOLUTION +/- 1 DEG. F ERROR +/- 2.5 DEG. F 8 CHANNELS SERIAL # 9440010

TYPE "T" DIGITAL PYROMETER NEWPORT MODEL 267-B TF-2 -150.0 TO +750 DEG. F RESOLUTION +/- 0.1 DEG. F ERROR +/- 0.56 DEG. F 8 CHANNELS SERIAL # 3021263 - 25

FUEL TEMP. PYROMETER NEWPORT MODEL 267-B TF-2 -150.0 TO +750 DEG. F RESOLUTION +/- 0.1 DEG. F ERROR +/- 0.56 DEG. F SERIAL # 2207514 - 25

AIR FLOW NOZZLE PRESSURE MERIAM INSTRUMENT CO. MODEL 30EB25 RANGE 0 TO 30 IN. WATER, 0.1 IN. WATER DIVISIONS LEFT SIDE SERIAL # W67993 RIGHT SIDE SERIAL # W69521

COMPRESSOR DISCHARGE AND NOZZLE BOX PRESSURE MERIAM INSTRUMENT CO. MODEL A-324 RANGE 0 TO 60 IN. HG., 0.1 IN. HG. DIVISIONS COMPRESSOR DISCHARGE LEFT SERIAL # 44F552 COMPRESSOR DISCHARGE RIGHT SERIAL # 44F548 NOZZLE BOX PRESSURE SERIAL # 44F559

FUEL FLOW ROTAMETER BROOKS ROTAMETER CO. TUBE TAPER 9M-600 LI TWIN FLOAT RANGE 0 TO 600 DIVISIONS BY 2

CELL PRESSURE FRONT AND BACK MERIAM INSTRUMENT MODEL 40GD10WM RANGE 0 TO 1 IN. WATER, 0.01 IN. DIVISIONS

DYNAMIC TORQUE / SPEED ACUREX CORPORATION MODEL 1206D SPEED RANGE (X10) 0-4000 RPM, +/- 10 RPM TORQUE RANGE 0 TO

700 FT-LB,   +/- 1 FT-LB HORSEPOWER (NOT USED) SERIAL # 1-278

STATIC TORQUE WALLACE AND TIERNAN MODEL FA-145 RANGE 0 TO 1000 FT-LB,   0-350 BY 1 FT-LB DIVISIONS 350-1000 BY 2 FT-LB DIVISIONS SERIAL #225B

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